Integration of deep geothermal energy and woody biomass conversion pathways in urban systems

Electronic Supplementary Information

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Contents

List of Figures

List of Tables

Acronyms

Φ	Humidity
HHV	Higher Heating Value
LHV	Lower heating value
MC	Moisture content
M	Molar mass
ar	As received
db	Dry basis
wb	Wet basis
BtL	Biomass To Liquids
CCGT	Combined-Cycle Gas Turbine
CEPCI	Chemical Engineering's Plant Cost Index
CHP	Cogeneration of Heat and Power
DHN	District Heating Network
EGS	Enhanced Geothermal System
FT	Fischer-Tropsch
GT	Gas Turbine
GWP	Global Warming Potential
HFO	Heavy Fuel Oil
HH	Human Health
LCA	Life Cycle Assessment
LFO	Light Fuel Oil
MILP	Mixed-Integer Linear Programming
MSW	Municipal Solid Waste
MSWI	Municipal Solid Waste Incineration
NG	Natural Gas
O&M	Operation and Maintenance
ORC	Organic Rankine Cycle
PHEV	Plug-in Hybrid Electric Vehicle
pkm	Passenger-kilometer
SFOS	Swiss Federal Office of Statistics
SiL	Services Industriels de Lausanne
SNG	Synthetic Natural Gas
TL	Transport Lausannois
UCTE	Union for the Co-ordination of Transmission of Electricity
WWT	Waste-Water Treatment
WWTP	Waste-Water Treatment Plant

1 Lausanne case study

The European urban system of Lausanne (Switzerland, 140,421 inhabitants in 2015) is taken as an example case study in this work. Figure 1 shows the energy flow Sankey diagram of the city for the year 2012, taken as reference in this study. The final energy consumption is broken down into its three main components: heating (59.9 %, including industry), electricity (22.9 %, including industry) and transportation (17.2 %). Cooling is negligible and thus not accounted for in this study. Industry has a small impact on the total final energy consumption (3.7 %) of the urban system. Fossil fuels (oil and natural gas) account for 59.0 % of the urban system's primary energy consumption, covering the largest share of the demand in the heating and in the transportation sectors.

A District Heating Network (DHN), covering 20.6 % of heating final energy consumption, is supplied by fossil fuel boilers (mainly running on natural gas), a Waste-Water Treatment Plant (WWTP) and a Municipal Solid Waste Incineration (MSWI) cogeneration power plant. Electricity demand is mainly satisfied by hydroelectricity (80.9 %), followed by nuclear (7.3 %), and smaller contributions from other renewable resources (biomass, solar and wind). There is currently no deployment of deep geothermal technologies, whereas biomass (woody biomass and dry sludge from waste water) accounts for 2.5 % of the primary energy consumption, with 15.4 kt (1 kt = 10^6 kg) of local woody biomass burned in the MSWI in the year 2012 out of a total potential estimated in the range of 50-100 kt/year[1].

The planned expansion of the DHN as well as the phasing out of nuclear power plants in Switzerland [28] present opportunities for a wider deployment of these two renewable resources as fossil fuel substitutes. The share of centralised heat production has a yearly growth rate of about 2 %. The DHN is forecast to satisfy about 45 % of the projected total heat demand by the year 2035.

[1]Sustainable potential of wood in the area of Lausanne, personal communication from the Services Industriels de Lausanne (SiL)

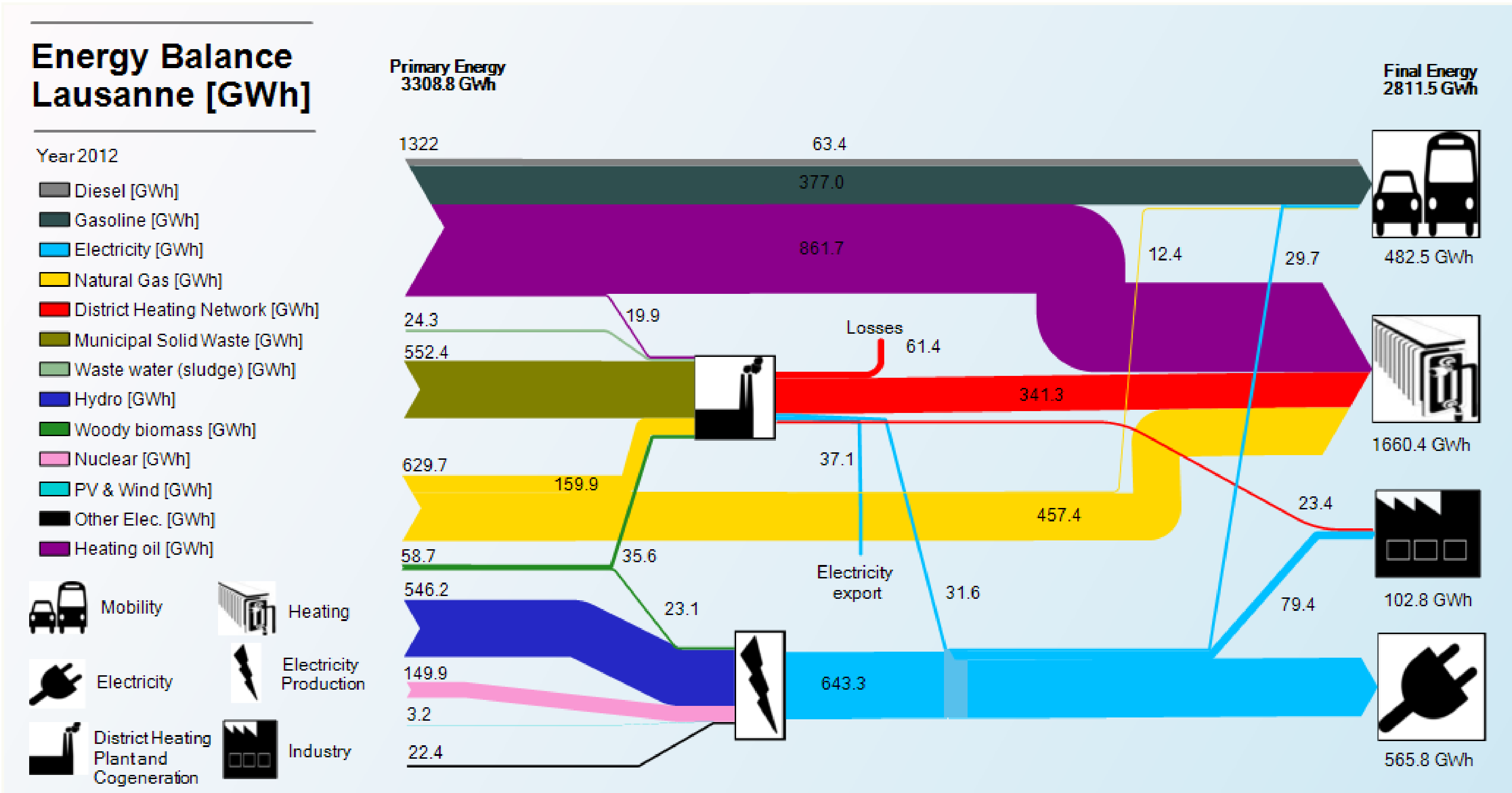

Figure 1: Energy flow Sankey diagram of the city of Lausanne (Switzerland) for the year 2012 (adapted from [18])

1.1 Excess heat from the MSWI

The MSWI of the city ("TRIDEL") is a cogeneration power plant, burning in 2012 161 kt of MSW and 15.4 kt of wet wood. In the same year, the total output of the power plant was 85.1 GWh_e of electricity and 261.6 GWh_{th} of heat. Out of the total production, 25.6 % of the electricity and 1.2 % of the heat are used to satisfy the internal energy requirements of the power plant [46].
As described in section 3.8.1, the waste is burned in a boiler. The produced steam is expanded in a 20 MW_e turbine and then drawn-off (175 °C) for high temperature industrial applications and district heating. As the waste input is rather constant over the year, the potential heat production in summer is higher than the urban heat demand. Thus, in summer the steam is expanded until ambient temperature to increase the electricity output.

A simplified flowsheeting model of the MSWI power plant has been developed in [18] assuming constant waste input over the year. The goal of this modeling effort was to reproduce the seasonal behavior of the power plant, thus evaluating the marginal efficiency of electricity production in periods of low heating demand. Marginal efficiency is here defined as the ratio between the increase in electricity production in summer over the reduction in heat supply in the same period. Results show that the marginal efficiency of electricity production is 14.7 %.

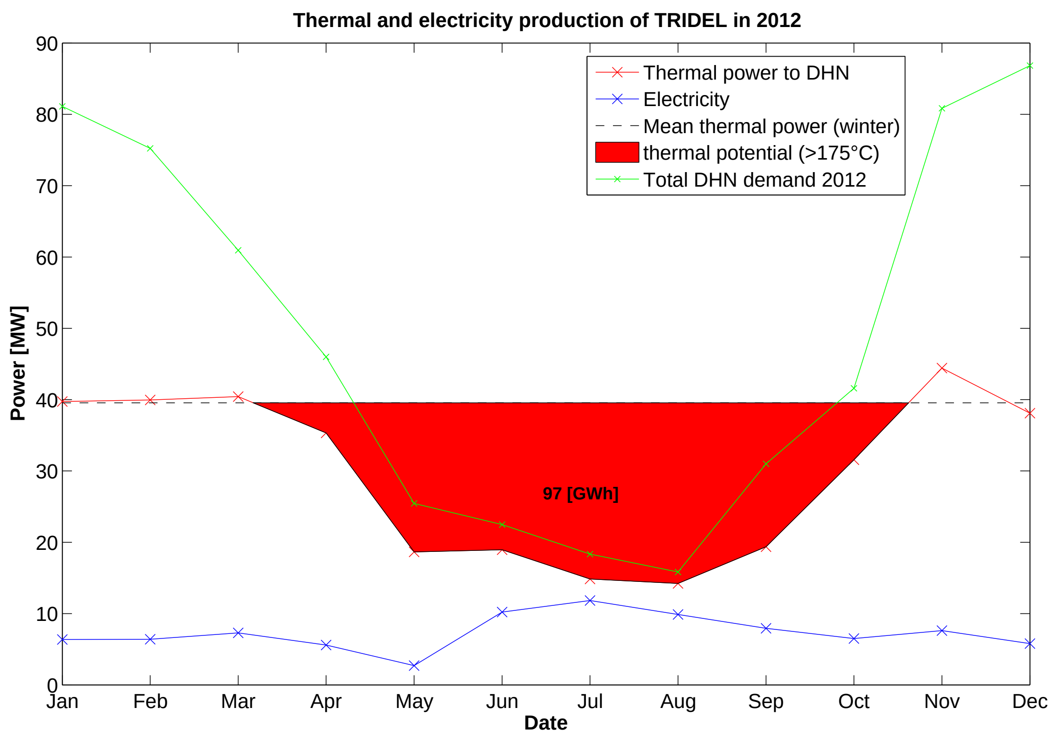

Figure 2: Lausanne MSWI thermal and electricity production compared to the DHN demand in the year 2012 [18]. The figure shows the high thermal potential available in summer, which is today converted to electricity at a low marginal efficiency.

The thermal and electrical production of the MSWI are compared in Figure 2 with the total DHN demand of Lausanne for the year 2012. The figure shows the mean monthly net power production compared to the

DHN demand (in green). The black dotted line is the net mean thermal power output in the winter period. The area in red represents the thermal power that could theoretically be produced in periods of low heating demand if the power plant was operated all the year in the winter operating configuration, i.e. without expansion down to ambient temperature. This "excess heat" corresponds to approximately 97 GWh_{th} at a temperature above 175 °C. It is used today in the second stage of the condensing turbine of the MSWI to produce electricity with a very low efficiency. This is due to the low heat demand of the DHN in summer.

In view of the planned future expansion of the DHN this heat could be used to supply the increased heat demand. Thus, in this work the winter mean operation conditions (38.65 MW thermal and 8.61 MW electric) are assumed for the whole year in the prospective scenarios. The auto consumption of the MSWI is accounted for in the model and is assumed constant over the year. In [27] it is shown that this heat would be sufficient to satisfy the projected DHN heat demand in the year 2035. When this is the case, the integration of geothermal resources generates an excess of heat in summer which can be integrated in biomass conversion processes.

1.2 Evolution of the energy system to 2035

The energy model used in this work takes the situation in the year 2012 as a reference. Nonetheless, as the integration of biomass and geothermal technologies represents a long term strategy of the city linked to the extension of the DHN, the evolution of the energy system to the year 2035 is considered. Some simplifying assumptions are made about the evolution of the Lausanne energy system between 2012 and 2035:

- Population growth: a 0.7 % yearly rate is assumed for the demographic growth, increasing the urban system population from 137,000 inhabitants in 2012 to 161,000 in 2035.
- Demand in energy services: the specific demand per capita in energy services for electricity and transportation is assumed to remain constant, with the share of Mpkm provided by public transportation increased to 28.5 % in 2035 and share repartition as in section 3.9. The total heating demand is assumed to remain constant due to the balanced effects of population growth and building efficiency. The DHN is assumed to cover 45 % of the heating end-uses, with an increased length of 170 km in 2035.
- Electricity production: the installation of a new $31MW_e$ Kaplan turbine is considered.
- For decentralized boilers, an increased share of the heat demand is satisfied by natural gas boilers (60 %), with 40 % satisfied by oil boilers.

2 MILP model

Section 2.2 of the main article illustrates the constraints of the optimization model. This section is complementary to it, as it details the sets, variables and parameters of the model in order to ensure reproducibility. For consistency, sets are written in all capital letters (e.g. "SET"), parameters in italic lowercase (e.g. "*parameter*"), variables in bold lowercase with capitalized first letter (e.g. "**Variable**")

2.1 Sets

Figure 3 shows the sets and subsets of the MILP formulation. The indices adopted in the figure are consistently used throughout the paper.

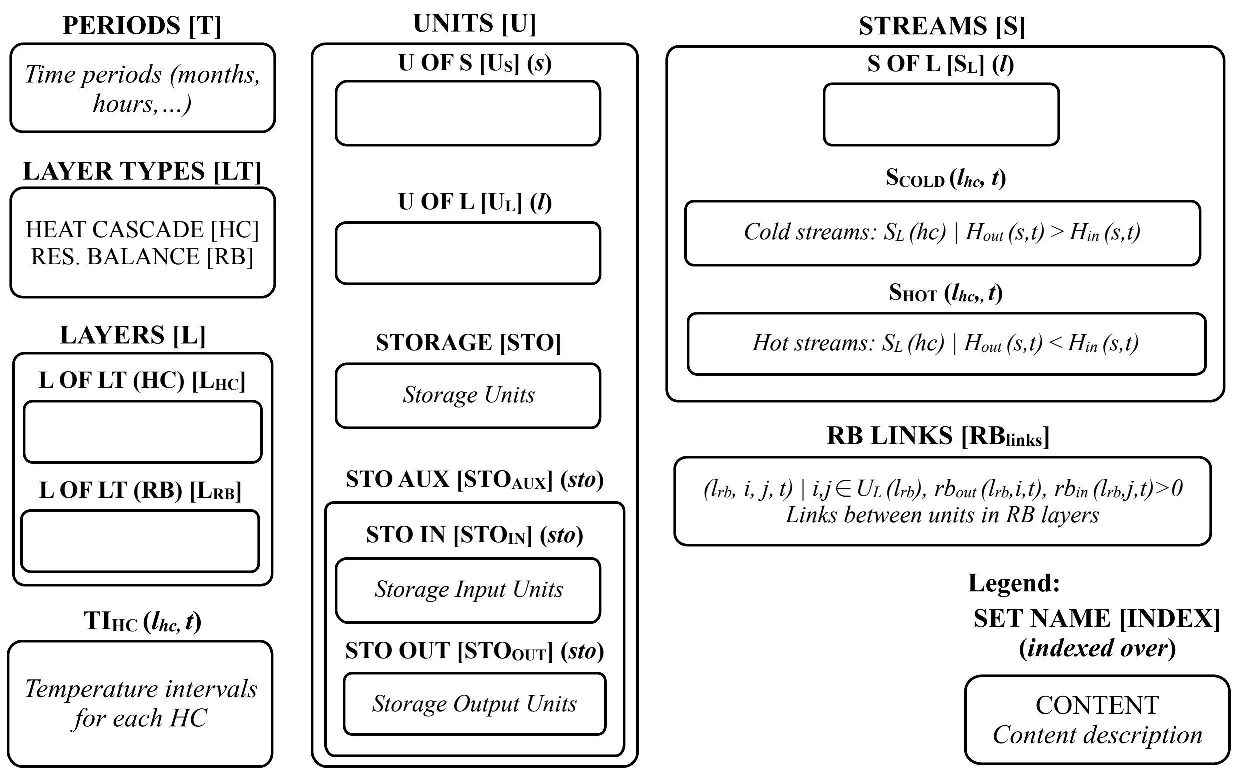

Figure 3: Sets of the MILP model with the corresponding indices

2.2 Parameters

Table 1 lists the model parameters, specifying their units and description.

2.3 Variables

Table 2 lists the model variables, specifying their units and description.

Table 1: Parameter list with description. Set indices as in Figure 3

Parameter	Units	Description
$t_{op}(t)$	[h]	Time periods duration
$f_{min}, f_{max}(u)$	[-]	Min/max $Mult_t(u,t)$ if u is used
$use_f(u,t) \in \{0,1\}$	[-]	Force use: If 1 then u must be used
$c_{inv,fix}(u)$	[MCHF/y]	Unit annualized fixed investment cost
$c_{inv,var}(u)$	[MCHF/y]	Unit ann. var. inv. cost if $Mult(u) = 1$
$c_{op,fix}(u)$	[MCHF/h]	Unit fixed operating cost
$c_{op,var}(u)$	[MCHF/h]	Unit var. op. cost if $Mult_t(u,t) = 1$
$T^*_{in}, T^*_{out}(s,t)$[a]	[K]	Streams input/output temperature
$H_{in}, H_{out}(s,t)$	[MW]	Streams input/output enthaply
$cp(s,t)$	[MW/K]	Heat capacity flowrate $:= \Delta H/\Delta T$
$T_{int}(l_{hc}, t, ti_{hc}(l_{hc}, t))$	[K]	Lower T of each temperature interval
$T_{max}(l_{hc}, t)$	[K]	$:= \max_{ti_{hc}(l_{hc},t)}(T_{int}(l_{hc}, t, ti_{hc}(l_{hc}, t)))$
$T_{min}(l_{hc}, t)$	[K]	$:= \min_{ti_{hc}(l_{hc},t)}(T_{int}(l_{hc}, t, ti_{hc}(l_{hc}, t)))$
δ	[K]	1e-5, used in heat cascade constraints
$rb_{in}(l_{rb}, u_l(l_{rb}), t)$	[MW][c]	RB input for units if $Mult_t(u,t) = 1$
$rb_{out}(l_{rb}, u_l(l_{rb}), t)$	[MW][c]	RB output for units if $Mult_t(u,t) = 1$
$\varepsilon(sto_{aux})$	[-]	Efficiency [0;1] of storage input/output

[a]Corrected temperatures: $T^* = T \pm \Delta T_{min}/2$ ($+$ if $s \in S_{COLD}$, $-$ if $s \in S_{HOT}$)

Table 2: Variable list with description. All variables are continuous and non-negative, unless otherwise indicated.

Variable	Units	Description
$\mathbf{Mult}(u)$	[-]	Unit size multiplication factor
$\mathbf{Mult_t}(u,t)$	[-][b]	Unit operation in each period
$\mathbf{Use}(u) \in \{0,1\}$	[-]	Unit use. If 0 unit is not purchased
$\mathbf{Use_t}(u,t) \in \{0,1\}$	[-]	Unit use in each period
$\mathbf{C_{op}}(u,t)$	[MCHF]	Unit operating cost in each period
$\mathbf{C_{inv}}(u)$	[MCHF/y]	Unit annualized investment cost
$\mathbf{Mult_s}(s,t)$	[-]	Stream multiplication factor
$\mathbf{R}(l_{hc}, t, ti_{hc}(l_{hc}, t))$	[MW]	Heat cascaded from ti to lower ones
$\mathbf{RB_{in}}(l_{rb}, u_l(l_{rb}), t)$	[MW][c]	Total RB input for units
$\mathbf{RB_{out}}(l_{rb}, u_l(l_{rb}), t)$	[MW][c]	Total RB output for units
$\mathbf{RB_{flow}}(rb_{links})$	[MW][c]	Total RB flow between units

[b]If $u \in STO$ it represents the level of the storage in energy or mass units
[c]Units as in corresponding layer: [t/h] if layer is in mass, [pkm/h] for mobility

3 Unit models

This section details models and data used in the study. The unit models represented in Figure 2 are characterized in terms of energy and mass balances, cost (operating and investment), and environmental impact (Global Warming Potential (GWP) and Human Health (HH)). Repartition of cost and Life Cycle Assessment (LCA) data between resources and technologies follows the methodology presented in section 2.3. LCA data are taken from the Ecoinvent database v3.2[2] [50] using the "allocation at the point of substitution" system method. As described in the main article (Section 2.3.2), GWP is assessed with the "GWP100a - IPCC2013" indicator, whereas HH impact is assessed with the "impact2002+ - human health" (expressed in points "pts") and "ecoscarcity 2013 - main air pollutants and PM" (expressed in ecopoints "UBP" - *Umweltbelastungspunkte*) indicators.

All costs are expressed in *real*[3] Swiss Francs for the year 2015 (CHF_{2015}). All cost data used in the model originally expressed in other currencies or referring to another year are converted to CHF_{2015} to offer a coherent comparison. The method used for the conversion is shown in Eq. 1.

$$\text{c}_{\text{inv}}\ [\text{CHF}_{2015}] = \text{c}_{\text{inv}}[C_y] \cdot \frac{\text{USD}_y}{C_y} \cdot \frac{\text{CEPCI}_{2015}\ [\text{USD}_{2015}]}{\text{CEPCI}_y\ [\text{USD}_y]} \cdot \frac{\text{CHF}_{2015}}{\text{USD}_{2015}} \tag{1}$$

Where C and y are the currency and the year in which the original cost data are expressed, respectively, USD is the symbol of American Dollars and the Chemical Engineering's Plant Cost Index (CEPCI) [11] is an index taking into account the evolution of the equipment cost (values are reported in Table 3). As an example, if the cost data are originally in EUR_{2010}, they are first converted to USD_{2010}, then brought to USD_{2015} taking into account the evolution of the equipment cost (by using the CEPCI), and finally converted to CHF_{2015}. The intermediate conversion to USD is motivated by the fact that the CEPCI is expressed in *nominal* USD.
Prices of resources and technologies are taken for the year 2015, under the assumption that the entire energy system is "rebuilt" in this year, and it will be operating in the same conditions in the future year taken as reference (2035). No future evolution of the investment cost of technologies and resources is accounted for. In the next sections, the total investment cost of the technologies is reported. In the Mixed-Integer Linear Programming (MILP) model, these investment costs are annualized based on the lifetime of the technologies by multiplying the total investment by the factor τ, calculated as in Eq. 2.

$$\tau = \frac{i(1+i)^{n_{tech}}}{(1+i)^{n_{tech}} - 1} \tag{2}$$

In which n_{tech} is the economic lifetime of the different technologies and i is the *real* discount rate . n_{tech} is assumed to be 25 years unless other data are found in the literature. The discount rate for the public investor is fixed at 3.215 %, average value from the low and high values proposed in [13], where the high value is based on the official discount rate for energy in Switzerland [36] and the lower value is the estimated discount rate for Swiss electricity producers.
In this framework, annualized investment cost of existing technologies is also accounted for. This is coherent with the fact that at the end of their lifetime these technologies need to be replaced. In this way, the cost of technologies is spread over their whole lifetime, whereas financial depreciation would only attribute this cost to their early years of operation, leaving an upfront investment cost to future generations.

[2] The database in consulted online: `http://www.ecoinvent.org`
[3] *Real* values are expressed at the net of inflation. They differ from *nominal* values, which are the actual prices in a given year, accounting for inflation.

Table 3: CEPCI values [11]

Year	**CEPCI**
1982	285.8
1990	357.6
1991	362.3
1992	367.0
1993	371.7
1994	376.4
1995	381.1
1996	381.7
1997	386.5
1998	389.5
1999	390.6
2000	394.1
2001	394.3
2002	395.6
2003	402.0
2004	444.2
2005	468.2
2006	499.6
2007	525.4
2008	575.4
2009	521.9
2010	550.8
2011	585.7
2012	584.6
2013	567.3
2014	576.1
2015	556.3

3.1 Resources

Resources and their properties are listed in Table 4.
Cost data refer to average values for Switzerland for the year 2015. For imported resources, such as heating oil, diesel, Natural Gas (NG) and electricity, the cost is taken at the city border, i.e. profit made by intermediate public service providers is not taken into consideration. Municipal Solid Waste (MSW) and dry sludge from Waste-Water Treatment (WWT) are considered free of charge as they would need to be collected anyway. The 2015 Union for the Co-ordination of Transmission of Electricity (UCTE) production mix LCA data are assumed for the electricity imports.
For GWP the impact associated to the resources includes the emissions related to their production, transport and use, under the simplifying assumption that, for fuels, the GWP of use is well represented by the emissions related to combustion and thus it is independent of the technology used. For human health and air quality this simplifying assumption is not suitable as these emissions are technology-dependent. Thus, for this category processing and transportation remain allocated to the resources, whereas combustion emissions are allocated to the technologies.

3.1.1 Woody biomass

Particular attention is given to the representation of biomass which refers here only to lignocellulosic biomass in the form of wood chips. The resource is represented by "wet wood" chips (humidity (Φ) = 50 %). The humidity (Φ), also called moisture content (MC) on a wet basis (wb), corresponds the mass of water [kg$_{H_2O}$] contained in 1 kg of wood [kg$_{wb}$]. As an example, 1 kg of wet wood (1 kg$_{wb}$) at $\Phi = 50$ % contains 0.5 kg$_{H_2O}$ and 0.5 kg of oven dry[4] wood [kg$_{db}$] ($\Phi = 0$ %). The reference lower heating value (LHV) on a dry basis (db) ($\Phi = 0$ %) is 19 MJ/kg [6], and the corresponding LHV on a wb is calculated using Eq. 3.

$$LHV_{wb} = LHV_{db} \cdot (1 - \Phi) - \Delta H_{vap} \cdot \Phi \qquad \left[\frac{MJ}{kg_{wb}}\right] \tag{3}$$

Where ΔH_{vap} is enthalpy of vaporization of water, equal to 2.443 MJ/kg [6]. In this work, when wood is represented in terms of power or energy equivalent, the wb representation is adopted unless otherwise stated. The LHV_{db} is calculated from the Higher Heating Value (HHV) by subtracting the energy of the water generated in the combustion reaction, as the LHV takes into account that this water is not condensed when leaving the system. Thus, the latent heat of condensation is not recovered as useful energy from the combustion process (Eq. 4).

$$LHV_{db} = HHV - \frac{c_H}{2} \cdot \Delta H_{vap} \cdot M_{H_2O} \qquad \left[\frac{MJ}{kg_{db}}\right] \tag{4}$$

Where c_H is the mass fraction of hydrogen in the biomass composition, and M is the molar mass.

[4] As a simplification, "dry wood" refers in the article to wood at $\Phi = 15$ %, "wet wood"to wood at $\Phi = 50$ %. Here the term "oven dry" is adopted to refer to wood at $\Phi = 0$ %. "Dry basis (db)" always indicates $\Phi = 0$ %.

Table 4: Resources properties

Resource	**LHV** [MJ/kg]	**Density** [kg/m^3]	**Price** [CHF$_{2015}$/MWh]	**GWP100a - IPCC2013**[a] [kgCO_2-eq./MWh]	**HH - Impact2002+**[b] [pts/MWh]	**ES2013**[b] [UBP/MWh]
Heating oil	42.90 [38]	843.1 [37]	86.55[c]	311	7.48e-03	1.76e+04
Diesel	43.00 [38]	832.0 [16]	157.0[d]	315	8.48e-03	1.94e+04
Petrol	42.60 [38]	745.0 [16]	173.6[e]	345	1.07e-02	2.48e+04
NG	47.76 [38]	0.760 [50]	60.20[f]	267	7.11e-03	1.57e+04
Electricity			105.6[g]	482	8.21e-02	8.23e+04
Wet wood (Φ= 50%)	8.279[h]	324.5[i]	47.58[j]	11.8[k]	1.22e-03	2.95e+03
MSW	12.35 [26]	-	0	150[l]	0	0
Dry sludge - WW	2.966 [26]	-	0	0[m]	0	0

[a] Impact associated to production, transport and combustion.

[b] Impact associated to production, transport.

[c] Average heating oil price for Jan-Nov 2015 for 800-1500 l consumers, corresponding to 0.8696 CHF$_{2015}$/L [42].

[d] Average Diesel price for Jan-Nov 2015, corresponding to 1.56 CHF$_{2015}$/L [41].

[e] Average 95 & 98 petrol price for Jan-Nov 2015, corresponding to 1.53 CHF$_{2015}$/L [41].

[f] It is assumed that the price for the City of Lausanne is twice the average import price Jan-Oct 2015 at the Swiss border (estimate based on personal communication from GazNat, May 2015. Import price data received by e-mail from the Swiss Federal Office of Statistics (SFOS) [40], Nov. 2015)

[g] Import and production price index data for a big industry >20 GWh/y, average for Jan-Oct 2015 (data received by e-mail from the SFOS [40], Nov. 2015).

[h] LHV on a wet basis (wb) calculated as in Eq. 3.

[i] Density calculated as the average of wet (Φ = 45-55 %) hardwood and softwood woodchips bulk density [6].

[j] Price calculated as the average of wet (Φ = 45-55 %) hardwood and softwood woodchips prices in Switzerland for the years 2014-2015 [49]. Does not include value-added tax (VAT).

[k] In the IPCC 2013 GWP indicator implementation in Ecoinvent, non-fossil CO and CH_4 are assigned positive emission coefficients as detailed in [8]. Thus, wood combustion has non-zero emissions in the model. Emissions associated to combustion are 3.67 kgCO_2-eq./MWh. These emissions are allocated to the resource, under the assumption that all wood is burned at some stage in all the conversion pathways, including the ones involving production of biofuels.

[l] GWP impact related to the treatment of MSW in an incineration plant, including auxiliary emissions due to the operation of the plant but not including its construction. This is not consistent with the other data presented in the table, however the incineration plant is the only technology treating MSW therefore associating the auxiliary emissions to the resource does not affect the results. Emissions related to production and transport of MSW are not accounted for.

[m] Emissions related to production, transport and combustion of dry sludge are not accounted for.

3.2 Energy demand

The energy demand of the city is divided into heating, electricity and mobility. Cooling demand is negligible in the studied urban system. Table 5 shows the values of the end-uses in energy services assumed for the City of Lausanne in 2035. As described in Section 1.2, the energy demand in 2035 is calculated based on the 2012 situation, assuming a constant total demand for heating and a constant *per capita* demand for mobility and electricity. For electricity and heating, average power values are considered for the different periods in order to account for the seasonal variation in energy demand. Mobility is assumed to be constant over the different periods.

Table 5: Characterization of end-uses in energy services for the City of Lausanne in 2035.

Period	**Duration** [h]	**Heating** [MW]		**Mobility** [Mpkm/y]		**Electricity** [MW]
		DHN	**Decentralized**	**Public**	**Private**	
Summer	2928	35.33	43.18	354.9	890.4	69.87
Winter	3624	124.6	152.3			97.57
Mid-season	2208	60.82	74.34			90.64
Peak	1e-04	211.9[a]	304.5[b]			146.5[c]

[a] Ratio between peak and winter demand as in [18]. Calculated based on DHN hourly production profile.
[b] Ratio between peak and winter demand assumed to be 2, as in [18].
[c] Ratio between peak and winter demand assumed to be 1.5, as in [18].

The annual consumption for heating and electricity is calculated based on data provided by the Services Industriels de Lausanne (SiL), the public energy service provider of the city. The seasonal repartition of the heating demand, assumed equal for centralized and decentralized heating, is calculated based on the DHN hourly production profile. The share of the heat demand satisfied by the DHN is 45 %.
Mobility is expressed in passenger-kilometers (pkms). Based on the data from SiL and Transport Lausannois (TL) Amblard [18] has calculated a specific mobility of 7735 pkm/ca. for the city in 2012, with a 19.5 % share of public mobility. In the year 2035, this share is assumed increased to 28.5 %. The specific mobility is lower than the national value as the latter includes as well walking, biking, trains and flights, which are not accounted for in this model.

3.3 Biomass technologies

3.3.1 Wood dryer

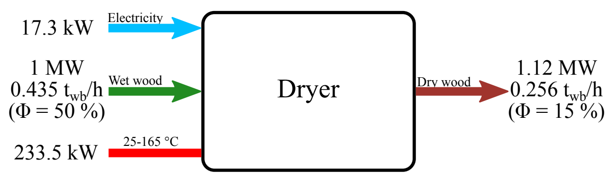

Figure 4: Wood dryer unit model.

The air wood dryer (Figure 4) has wood at $\Phi = 50$ % as an input, and wood at $\Phi = 15$ % ($LHV = 15.7835$ MJ/kg$_{wb}$) as an output. The flowsheet model is originally developed in Belsim Vali™ by Gassner [19], while the cost functions are based on data from producers elaborated by Peduzzi [17]. Cost and emissions data are reported in Table 6.
In the main article the concept of drying "efficiency" is adopted. This is defined as the theoretical heat needed to evaporate the water contained in the wood ($\dot{m}_{H_2O}$) over the actual heat needed for the drying process ($\dot{Q}^{+}_{drying}$). Eq. 5 calculates the efficiency for the dryer as in Figure 4.

$$\varepsilon_{drying} = \frac{\dot{m}_{H_2O} \cdot \Delta H_{vap}}{\dot{Q}^{+}_{drying}} = \frac{(\dot{m}_{wood_{in}} - \dot{m}_{wood_{out}}) \cdot \Delta H_{vap}}{\dot{Q}^{+}_{drying}} = 0.52 \tag{5}$$

Where the amount of water evaporated is equal to the weight difference between input and output wood mass flow rate (kg$_{wb}$/s). Biomass chemical conversion processes with "wet" wood as an input ($\Phi = 50$ %) are modeled using the same dryer. The higher efficiency in that case (62 %) is due to the fact that, when used in biomass chemical conversion processes, the dryer can reach a higher temperature (200 °C). In the model the external dryer is limited to 165 °C to achieve better integration with the available geothermal heat.

Table 6: Wood dryer parameters

	Value	**Units**	**References**
Reference size	3-18	MW_{in}	
$c_{inv,fix}$ [a]	1.710e5	CHF_{2015}	[17]
$c_{inv,var}$ [a]	6.457e4	CHF_{2015}/MW_{in}	[17]
$c_{op,fix}$ [b]	0.976	CHF_{2015}/h	
$c_{op,var}$ [b]	0.369	CHF_{2015}/MWh_{in}	
Lifetime	50	y	[50]
GWP100a$_{C,E}$ [c]	7.455e3	$kgCO_2$-eq./MW_{in}	
Impact2002+$_{C,E}$ [c]	3.699	pts/MW_{in}	
ES2013$_{C,E}$ [c]	7.313e6	UBP/MW_{in}	

[a] Investment cost regression between 2.4 and 18.4 MW_{in} based on the Wyssmont™ dryer cost reported in [17]. In the model, the regression is assumed valid in a larger range as the maximum size of the drying process is 79 MW which is obtained when all the wood is dried in the summer.
[b] Operation and Maintenance (O&M) assumed as 5 % of c_{inv} over 8760 hours.
[c] Calculated according to the size estimate reported by [17], considering steel as a construction material from [50]. Impacts only related to construction of the dryer. Operation impacts are not accounted for.

3.3.2 Fast pyrolysis for bio-oil production

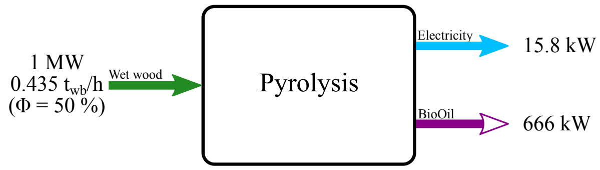

Figure 5: Pyrolysis unit model.

This model is adapted from the work by [34], presenting the performance analysis of a biomass fast pyrolysis biofuel production unit with electric power generation. In order to report the data coherently, the data in [34] are scaled under the simplifying assumption that the power input on a *wb* at $\Phi = 25$ % ($LHV = 13.050$ MJ/kg$_{wb}$), as considered in [34], is equivalent to the power input on a *wb* at $\Phi = 50$ %, as considered in this study. The LHV of the bio-oil is calculated according to Boie's correlation [7] and the compositions reported by [9] (mass fraction of carbon, hydrogen and oxygen on a *db* of 0.56, 0.06 and 0.38, respectively), yielding 15.247 MJ/kg on a wet basis (*wb*). Cost data are also adapted from the work by [34] according to the procedure described at the beginning of section 3, whereas O&M costs are assumed to be 5 % of the investment. As further detailed in section 3.5.2, when bio-oil is used in combustion processes, HH emissions are considered as an average between Light Fuel Oil (LFO) and Heavy Fuel Oil (HFO) (on an energy basis). This simplifying assumption is based on the study by Lehto et al. [25]. Cost and emissions data are reported in Table 7. The possibility of using char to displace synthetic fertilizers is not considered in this study as in the model considered the solid char is burnt in a combustion unit.

Table 7: Fast pyrolysis parameters

	Value	**Units**	**References**
Reference size	10	MW_{in}	[34]
$c_{inv,fix}$	-	CHF_{2015}	
$c_{inv,var}$	9.559e5	CHF_{2015}/MW_{in}	adapted from [34]
$c_{op,fix}$	-	CHF_{2015}/h	
$c_{op,var}$ [a]	5.46	CHF_{2015}/MWh_{in}	
Lifetime	25	y	
GWP100a$_{C,E}$ [b]	1.080e4	$kgCO_2$-eq./MW_{in}	
Impact2002+$_{C,E}$ [b]	4.089	pts/MW_{in}	
ES2013$_{C,E}$ [b]	8.084e6	UBP/MW_{in}	

[a] O&M assumed as 5 % of c_{inv} over 8760 hours.
[b] Calculated according to the size estimate reported by [17] for a dryer, considering steel as a construction material from [50]. Impacts only related to construction of the pyrolysis reactor. Operation impacts are not accounted for.

3.3.3 Fischer-Tropsch synthesis from biomass gasification

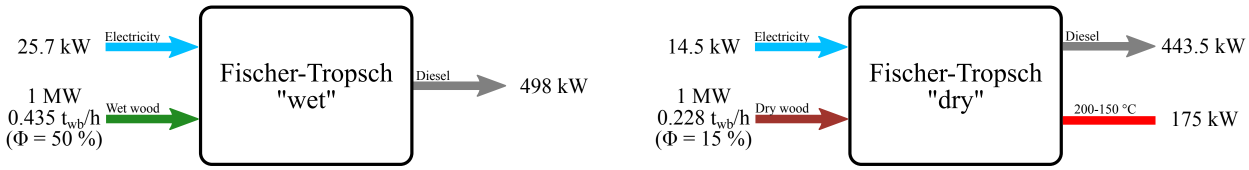

Figure 6: Fischer-Tropsch unit models for wet and dry wood input.

The Biomass To Liquids (BtL) models considered in this study consist in the synthesis of Fischer-Tropsch (FT) fuels from lignocellulosic biomass and are described in detail in [17]. The main process considered in the present study is a base case process using entrained flow gasification. The first step is the pretreatment where raw biomass (50 % or 15 % Φ) is dried, torrefied, and ground into fine particles. The biomass particles are then gasified in a pressurized (30 bar) steam-oxygen blown entrained flow gasifier. The synthesis gas produced, consisting mainly of H_2, CO, CO_2 is cooled by a water quench and cleaned by a scrubber. A water gas shift reactor is used to adjust the H_2-to-CO ratio and CO_2 is removed by amine scrubbing in order to satisfy the requirements of the FT synthesis where the liquid hydrocarbon fuels are produced. Process integration allows heat recovery and the co-production of electricity which is used to partly satisfy the requirement of the process. In the model, it is assumed that the produced FT fuels have the same properties as diesel.
This model is adapted for this study and used to represent two different configurations. The first process, represented on the left in Figure 6 and Table 8, has wet wood ($\Phi = 50$ %) as an input. The second process, represented on the right in Figure 6 and Table 8, uses biomass which is delivered at the conversion facility at $\Phi = 15$ % by an external dryer. The amount of heat used for wood drying in the first process ("FT wet") is made available to supply the DHN in the second configuration ("FT dry").
In both cases cost data is obtained by a linear regression of the costs of plants between 15 and 45 MW input of biomass (on a LHV_{db}). It should be underlined that these processes are very small compared to similar processes reported in the literature, generally ranging between 200 and 400 MW_{in} and also reaching over 1000 MW_{in} to benefit from economies of scale [22]. The small capacity is considered here according to the biomass availability for the city of Lausanne to study the interest of the implementation of a reduced size facility, if such an option will be feasible in the future. As for the technologies presented in the previous sections, the data is normalized to a biomass input of 1 MW (LHV_{wb}). The comparison of the two processes shows that the "FT dry" process using biomass at $\Phi = 15$ %, with the same input of 1000 kW (LHV_{wb}) as the "FT wet" process (using $\Phi = 50$ % biomass), is actually processing less biomass in terms of mass on a dry basis (db). This is the reason why the conversion to the FT fuel, on an wb energy basis, is smaller. The conversion on a db is the same. In the case of the "FT dry" process, the lower electricity requirement is due to the removal of the dryer unit.

Table 8: FT synthesis from biomass gasification parameters

	Value		**Units**	**References**
	FT wet ($\Phi = 50$ %)	**FT dry ($\Phi = 15$ %)**		
Reference size	15-45		$MW_{db,\text{in}}$	
$c_{\text{inv,fix}}$ [a]	4.143e7	3.997e7	CHF_{2015}	[17]
$c_{\text{inv,var}}$ [a]	2.360e6	1.955e6	$CHF_{2015}/MW_{\text{in}}$	[17]
$c_{\text{op,fix}}$ [a]	217.8	212.5	CHF_{2015}/h	[17]
$c_{\text{op,var}}$ [a]	15.7	13.5	$CHF_{2015}/MWh_{\text{in}}$	[17]
Lifetime	25		y	
$GWP100a_{C,E}$ [b]	4.016e4	3.581e4	$kgCO_2$-eq./MW_{in}	
$Impact2002+_{C,E}$ [b]	16.96	15.12	pts/MW_{in}	
$ES2013_{C,E}$ [b]	3.353e7	2.990e7	UBP/MW_{in}	
$GWP100a_{O}$ [c]	6.940e-1		$kgCO_2$-eq./$MWh_{db,\text{in}}$	
$Impact2002+_{O}$ [c]	1.495e-3		pts/$MWh_{db,\text{in}}$	
$ES2013_{O}$ [c]	4.806e3		UBP/$MWh_{db,\text{in}}$	

[a] Linear regression of cost data in [17], where they are obtained for a 200-400 MW_{in} production plant.

[b] Emissions associated to technology construction and end-of-life. Due to lack of data for a full LCA, emissions are assumed equal to the gasification to Synthetic Natural Gas (SNG) process.

[c] Emissions associated to technology operation, excluding combustion for GWP (allocated to the resource). Due to lack of data for a full LCA, emissions are assumed equal to the gasification to SNG process.

3.3.4 Synthetic Natural Gas production from biomass gasification

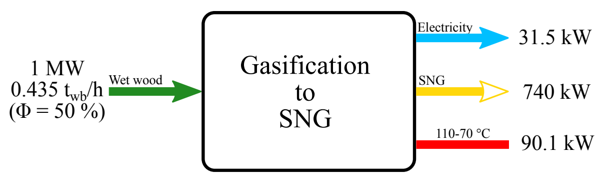

Figure 7: Gasification to SNG unit model.

The model of SNG production from woody biomass gasification (Figure 7) is adapted from [14]. In this process, biomass is dried and gasified to produce syngas, a gas mixture mostly made of hydrogen (H_2), carbon monoxide (CO), carbon dioxide (CO_2), and methane (CH_4). The syngas is cooled and cleaned of tars and other contaminants. This gas is then compressed and catalytically reacted in a methanation reactor to produce a gas mixture composed primarily of methane and carbon dioxide. Finally, the gas is purified and the carbon dioxide removed, in order to produce SNG that matches the requirements for injection into the Natural Gas (NG) network. Thus, in the model it is assumed that the produced SNG fuel has the same properties as fossil NG.
In [14] data for two SNG production plants are reported. The size of these installations is 40.5 MW_{in} ("Gazobois" project) and 135 MW_{in} (input biomass at $\Phi = 50$ %), respectively. Mass and energy balances are taken from these installations. The temperature level of the excess useful heat is assumed to be high enough to partially supply the city's DHN. Investment cost data are extrapolated from with data for a $20MW_{\text{in}}$ size with an exponential relation. Cost and emissions data are reported in Table 9.

Table 9: Gasification to SNG parameters

	Value	**Units**	**References**
Reference size	20	MW_{in}	
$c_{inv,fix}$	-	CHF_{2015}	
$c_{inv,var}{}^{a}$	2.168e6	CHF_{2015}/MW_{in}	[14]
$c_{op,fix}$	-	CHF_{2015}/h	
$c_{op,var}{}^{b}$	12.62	CHF_{2015}/MWh_{in}	[14]
Lifetime	25	y	
$GWP100a_{C,E}{}^{c}$	4.016e4	$kgCO_2$-eq./MW_{in}	
$Impact2002+_{C,E}{}^{c}$	16.96	pts/MW_{in}	
$ES2013_{C,E}{}^{c}$	3.353e7	UBP/MW_{in}	
$GWP100a_{O}{}^{d}$	6.940e-1	$kgCO_2$-eq./$MWh_{db,in}$	[20]
$Impact2002+_{O}{}^{d}$	1.495e-3	pts/$MWh_{db,in}$	[20]
$ES2013_{O}{}^{d}$	4.806e3	UBP/$MWh_{db,in}$	[20]

[a] Exponential extrapolation of cost data in [14].

[b] O&M are 5.1 % of the total investment cost per year, over 8760 h.

[c] Emissions associated to technology construction and end-of-life. Due to lack of data for a full LCA, assuming sum of emissions of a dryer unit, a pyrolysis unit for pre-treatment, and a gasifier. Multiplied by a factor 2 to account for emissions of other parts of equipment (cleaning, methanation, purification).

[d] Emissions associated to technology operation, excluding combustion for GWP (allocated to the resource). Calculated using the impact of gasification, plus adding the operation impacts of gas cleaning, methanation and purification (RME, catalysts (ZnO, Ni, Al_2O_3), limestone and gypsum) as in [20].

3.4 Geothermal resources and technologies

3.4.1 Geothermal resources

The City of Lausanne does not present particularly favorable geological characteristics in terms of geothermal resources (Figure 8). The geothermal gradient in the area is 0.03 °C/m [43]. In this work, deep aquifers and Enhanced Geothermal Systems (EGSs) are considered. For aquifers, the Muschelkalk aquifer (3.8 km depth, [51] is considered). The Malm aquifer (2 km depth) is not included in this case study as its temperature level is too low in comparison to the temperature of the city's DHN. For EGS three different depths are considered: 4.2 km (upper limit of the crystalline *stratum*), 5 km and 6 km. Table 11 characterizes the considered resources at different depths in terms of total heat extracted, pumping power, water expected mass flow rate, well temperature (T_{well}), total investment cost (including stimulation, exploration, fluid distribution and drilling), and cost for O&M. Technical parameters for the wells are average values over the lifetime calculated with the software environment GEOPHIRES [5], unless otherwise specified. The same software environment is also used for cost data estimation. The lifetime of the wells is assumed to be 30 years, the reinjection temperature is 70 °C, the pump efficiency is 80 % and the capacity factor is 90 %. It is assumed that 2 wells are needed for an aquifer and 3 wells are needed for an EGS.
Emissions related to drilling and operation of the wells are calculated in the post-computation phase according to the LCA methodology presented in [20] (Table 10).

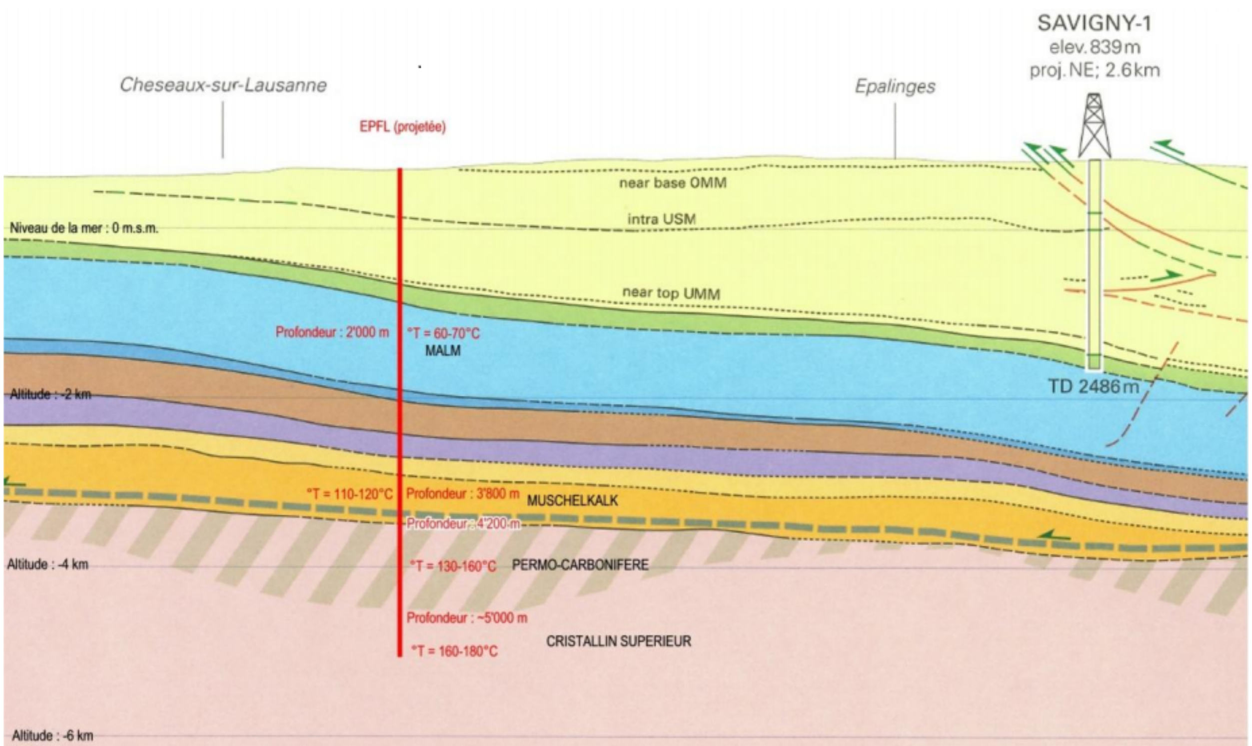

Figure 8: Geological profile of the City of Lausanne [43].

Table 10: Geothermal resources and energy conversion cycles emission parameters, calculated based on the LCA methodology presented in [20].

		LCA (*C*,*E*)[a]			LCA (*O*)[b]		
		GWP100a	**Impact2002+**	**ES2013**	**GWP100a**	**Impact2002+**	**ES2013**
		[kgCO_2-eq./u]	[pts/u]	[UBP/u]	[kgCO_2-eq./h]	[pts/h]	[UBP/h]
Resources	Aquifer 3.8 km	2.003e6	5.781e2	1.187e9	2.304e-4	9.657e-8	1.860e-1
	EGS 4.2 km	6.069e6	1.760e3	3.650e9	1.184e1	3.440e-3	7.421e3
	EGS 5 km	6.875e6	1.993e3	4.131e9	1.210e1	3.419e-3	7.381e3
	EGS 6 km	7.871e6	2.279e3	4.724e9	1.166e1	3.366e-3	7.278e3
Cycles	ORC 3.8 km	1.205e5	2.499e1	5.141e7	1.510	1.553e-4	3.222e2
	ORC 4.2 km	4.773e5	6.905e1	1.383e8	9.027	4.126e-4	8.463e2
	ORC 5 km	6.184e5	8.592e1	1.713e8	1.210e1	5.105e-4	1.044e3
	ORC 6 km	8.711e5	1.275e2	2.520e8	1.704e1	7.603e-4	1.538e3
	Kalina 6 km	2.944e5	7.904e1	1.653e8	1.862	4.999e-4	1.042e3

[a] Emissions related to construction and end-of-life of one unit (u). For resources a unit is a well, for cycles it is one cycle.
[b] Operating impact per one unit, over 7884 h (90 % capacity factor).

Table 11: Geothermal resources parameters.

	Heat[a]	**Pumping**	**Flow rate**	$\mathbf{T_{well}}$	$\mathbf{c_{inv,fix}}$	$\mathbf{c_{op,var}}$
	[kW_{th}]	[kW_e]	[kg/s]	[°C]	[CHF_{2015}/u]	[CHF_{2015}/h][b]
Aquifer 3.8 km	2544	3.50 [5]	13.5 [43]	115 [43]	2.143e7 [5]	4.964e1 [5]
EGS 4.2 km	23029	1231 [5]	100 [21]	125 [5]	3.731e7 [5]	1.756e2 [5]
EGS 5 km	31403	1180 [5]	100 [21]	145 [5]	4.836e7 [5]	2.287e2 [5]
EGS 6 km	41870	1053 [5]	100 [21]	170 [5]	6.370e7 [5]	3.001e2 [5]

[a] Calculated based on T_{well} and reinjection temperature of 70 °C.
[b] O&M cost per one well, over 7884 h (90 % capacity factor).

3.4.2 Energy conversion cycles

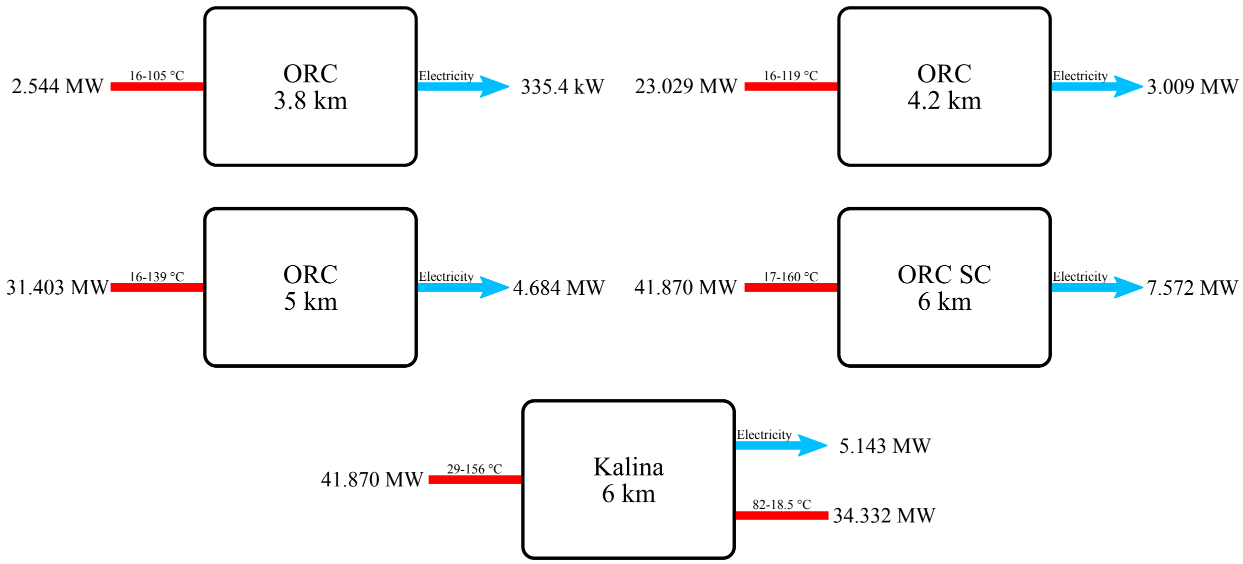

Figure 9: Simplified input-output representation of the geothermal ORC and Kalina cycles models.

The energy conversion cycles associated with the geothermal resources (Figure 9) are taken from the optimal configurations presented in [21]. For electricity production, Organic Rankine Cycles (ORCs) are considered for the resources shallower than 5 km with a single-loop configuration, while a supercritical (SC) cycle is chosen for the 6 km EGS. The high temperature of the city's DHN makes cogeneration with geothermal resources an unoptimal solution. For this reason, only a Kalina cogeneration cycle at 6 km is chosen, being the only one with temperature levels able to partially satisfy the network demand. ORCs use R134a as working fluid, whereas Kalina cycles use a H_2O/NH_3 mixture. The cyles are originally modeled with the flowsheeting software Belsim VALI^{TM} and optimized for each individual geothermal resource. The thermal streams corresponding to the optimal configurations are included in the MILP model. Figure 9 offers a simplified input-output representation of the cycles, taking into account only the net heat requirement/surplus for the thermal streams. To calculate the efficiency, the power available from the corresponding geothermal resources is taken as input. ORCs are not used in cogeneration, so the excess low-temperature heat is rejected to the environment. For the Kalina cycle, the thermal production shown in the figure corresponds to the condensation stream.
Investment costs are calculated based on a recent report for Switzerland [23], indicating a reference investment cost of 3000 USD_{2010}/kW_e (2891 CHF_{2015}/kW_e) for a 13 MW_e ORC installation. The investment cost has been scaled for the different cycles in this work using an exponential relation with an exponent of 0.9, as indicated in the report. In the lack of better data, the same scaling has been applied also for the Kalina cycle. Due to the lower electrical efficiency of the latter, this leads to higher specific investment cost for this cycle, as reported in [23]. The report indicates a lifetime of 30 years for the cycles. O&M costs are conservatively assumed to be 5 % of the total investment cost per year, based on [35][24][5]. Emissions related to drilling and operation of the wells are calculated in the post-computation phase according to the LCA methodology presented in [20] (Table 10).

3.5 Boilers

3.5.1 Centralized and decentralized NG boilers

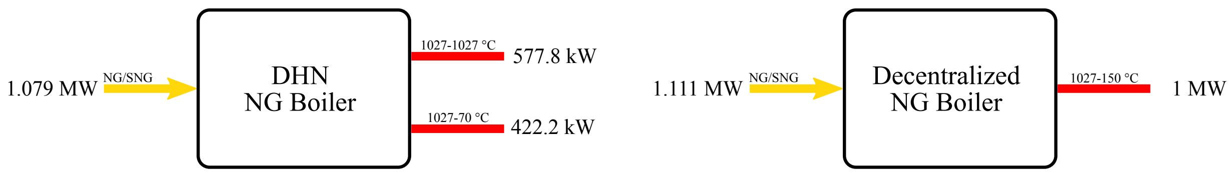

Figure 10: Centralized and decentralized NG boiler unit models.

These boiler unit models (Figure 10) can have both fossil NG and SNG as inputs, which are assumed to have the same performance in terms of efficiency and the same emissions (GWP combustion emissions are allocated to the resources). The boilers electricity consumption is neglected. The DHN boiler is modeled in Belsim VALI$^{\mathrm{TM}}$. The ideal efficiency on a *LHV* basis is 97.6 % and 5 % losses are assumed. The fumes reach an output temperature of 70 °C, and a distinction is made between the radiative and convective component of the heat production. For the decentralized boiler an overall efficiency of 90 % is assumed. In the model, the share of decentralized NG boilers is fixed in order to supply 60 % of the decentralized heat demand. Cost data are taken from [30] by logarithmic regression in the range 0.02-10 $\mathrm{MW_{th}}$. Cost and emission data are reported in Table 12.

Table 12: NG-SNG DHN and decentralized boilers parameters

	Value		Units	References
	DHN	**Decentralized**		
Reference size	5-20	0.01-0.03	$\mathrm{MW_{th}}$	
$c_{\mathrm{inv,fix}}$	-		$\mathrm{CHF_{2015}}$	
$c_{\mathrm{inv,var}}{}^{a}$	6.289e4	1.693e5	$\mathrm{CHF_{2015}/MW_{th}}$	[30]
$c_{\mathrm{op,fix}}$	-		$\mathrm{CHF_{2015}/h}$	
$c_{\mathrm{op,var}}{}^{b}$	3.145e-1	1.270	$\mathrm{CHF_{2015}/MWh_{th}}$	[30]
Lifetime	25	20	y	
GWP100a$_{C,E}$	2.590e3^{c}	2.109e4^{d}	$\mathrm{kgCO_2\text{-}eq./MW_{th}}$	
Impact2002+$_{C,E}$	8.401e-1^{c}	6.625^{d}	$\mathrm{pts/MW_{th}}$	
ES2013$_{C,E}$	1.884e6^{c}	1.285e7^{d}	$\mathrm{UBP/MW_{th}}$	
GWP100a$_{O}{}^{e}$	-		$\mathrm{kgCO_2\text{-}eq./MWh_{in}}$	
Impact2002+$_{O}{}^{e}$	7.060e-4		$\mathrm{pts/MWh_{in}}$	
ES2013$_{O}{}^{e}$	1.835e3		$\mathrm{UBP/MWh_{in}}$	

[a] Based on logarithmic regression on cost data in the range 0.02-10 $\mathrm{MW_{th}}$.
[b] For DHN O&M are 2 % of investment cost, for decentralized 3 % of investment cost. 4000 h/y of operation.
[c] Assumed equal to DHN wood boiler (Table 14).
[d] Assumed equal to decentralized oil boiler (Table 13).
[e] Operation impacts for a decentralized NG boiler.

3.5.2 Centralized and decentralized Oil-BioOil boilers

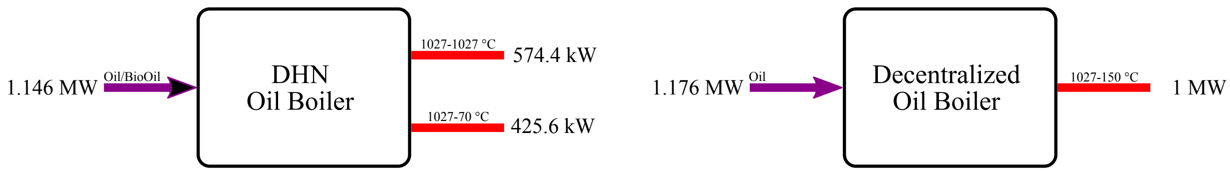

Figure 11: Centralized and decentralized Oil-BioOil boiler unit models.

The DHN boiler can have both fossil LFO and BioOil as inputs, which are assumed to have the same performance in terms of efficiency. The DHN boiler is modeled in Belsim VALI^{TM}. The ideal efficiency on a *LHV* basis is 96.95 % for BioOil assuming the composition as in section 3.3.2, and 10 % losses are assumed. The fumes reach an output temperature of 70 °C, and a distinction is made between the radiative and convective component of the heat production. The decentralized boiler model has only fossil oil as input. For the decentralized boiler an overall efficiency of 85 % is assumed. The boilers electricity consumption is neglected. Cost data are assumed equal to the NG boilers (Table 12). HH operating emissions are different for fossil oil and BioOil combustion. For the latter, HH emissions are considered as an average between LFO and HFO (based on the same input energy basis). This simplifying assumption is based on the study by Lehto et al. [25]. Cost and emission data are reported in Table 13.

Table 13: Oil and decentralized boilers parameters

	Value			**Units**	**References**
	DHN		**Decentralized**		
	LFO	**BioOil**			
Reference size	5-20		0.01-0.03	MW_{th}	
$c_{inv,fix}$	-		-	CHF_{2015}	
$c_{inv,var}$ [a]	6.289e4		1.693e5	CHF_{2015}/MW_{th}	[30]
$c_{op,fix}$	-		-	CHF_{2015}/h	
$c_{op,var}$ [a]	3.145e-1		1.270	CHF_{2015}/MWh_{th}	[30]
Lifetime	25		20	y	
$GWP100a_{C,E}$	2.590e3 [b]		2.109e4 [c]	$kgCO_2$-eq./MW_{th}	
$Impact2002+_{C,E}$	8.401e-1 [b]		6.625 [c]	pts/MW_{th}	
$ES2013_{C,E}$	1.884e6 [b]		1.285e7 [c]	UBP/MW_{th}	
$GWP100a_{O}$	-		-	$kgCO_2$-eq./MWh_{in}	
$Impact2002+_{O}$	3.070e-3 [d]	1.298e-2 [e]	3.592e-3 [f]	pts/MWh_{in}	
$ES2013_{O}$	8.262e3 [d]	3.096e4 [e]	9.196e3 [f]	UBP/MWh_{in}	

[a] Assumed equal to NG boilers (Table 12).
[b] Assumed equal to DHN wood boiler (Table 14).
[c] Linear regression between impact data in the range 10-100 kW_{th} from [50].
[d] Operation impact data for a 100 kW_{th} LFO boiler.
[e] Average impact between 100 kW_{th} LFO and 1 MW_{th} HFO boilers from [50]. Simplifying assumption based on [25].
[f] Operation impact data for a 10 kW_{th} LFO boiler.

3.5.3 Centralized wet and dry wood boilers

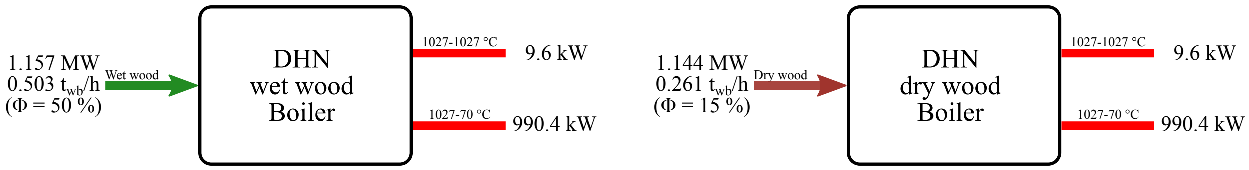

Figure 12: Centralized wet and dry wood boiler unit models.

The DHN wood boiler (Figure 12) is modeled to be powered with either wet wood ($\Phi = 50$ %) or dry wood ($\Phi = 15$ %). The model, realized with the flowsheeting software Belsim VALI^{TM}, is used in order to calculate the variation of efficiency between the combustion of wet wood and dry wood, considering a stack temperature of 70 °C. Losses are considered as 10 % of the heat output and the boilers electricity consumption is neglected. A distinction is made between the radiative and convective components of the heat production. The ideal efficiency on a LHV wet basis (wb) is 96.05 % in the case of wet wood, and 97.11 % in the case of dry wood. Cost data are taken from [30] by logarithmic regression on cost data in the range 0.02-20 MW_{th}. Operating emission data are taken from [50] for a state-of-the-art 1 MW_{th} boiler burning wood chips at $\Phi = 44.4$ %. Due to lack of emission data allowing to differentiate between wet and dry wood combustion, the same values on a db are assumed for the two cases. Cost and emission data are reported in Table 14.

Table 14: Centralized wet and dry wood boilers parameters

	Value	**Units**	**References**
Reference size	5-20	MW_{th}	
$c_{inv,fix}$	-	CHF_{2015}	
$c_{inv,var}$ [a]	1.230e5	CHF_{2015}/MW_{th}	[30]
$c_{op,fix}$	-	CHF_{2015}/h	
$c_{op,var}$ [b]	6.150e-1	CHF_{2015}/MWh_{th}	[30]
Lifetime	25	y	
$GWP100a_{C,E}$ [c]	2.590e3	$kgCO_2$-eq./MW_{th}	
Impact2002+$_{C,E}$ [c]	8.401e-1	pts/MW_{th}	
$ES2013_{C,E}$ [c]	1.884e6	UBP/MW_{th}	
$GWP100a_O$	-	$kgCO_2$-eq./$MWh_{db,in}$	
Impact2002+$_O$	1.615e-2	pts/$MWh_{db,in}$	
$ES2013_O$	1.848e4	UBP/$MWh_{db,in}$	

[a] Based on logarithmic regression on cost data in the range 0.02-20 MW_{th}.
[b] O&M are 2 % of investment cost over 4000 h/y of operation.
[c] Based on data for 300 kW_{th} and 1 MW_{th} wood chips boilers. Extrapolated by exponential regression.

3.6 Electricity production & Cogeneration (CHP)

3.6.1 Hydroelectricity

In 2012, hydroelectricity supplied 79.9 % of the total urban system electricity demand. The largest share of electricity production comes from the run-of-river power plant located in Lavey. It currently consists of three Kaplan turbines, each with a plate capacity of 31 MW_e, producing about 400 GWh_e/y. By 2035, a new unit will be installed and an increase of 75 GWh_e/y in production is expected. The power plant is modeled by Amblard [18] based on the information available in [32], estimating as well the seasonal variations. In the model it is assumed that hydroelectricity has priority over the other technologies, therefore the average production is fixed in each period to the values reported in Table 15. Cost and emission data are reported in Table 16.

Table 15: Fixed hydroelectricity power production in each period.

Period	**Hydroelectricity production** [MW_e]
Summer	56.82
Winter	45.85
Mid-season	75.33
Peak	124.0[a]

[a] Assuming that the new turbine has as well a 31 MW_e plate capacity.

Table 16: Hydroelectricity parameters

	Value	**Units**	**References**
$c_{inv,fix}$	-	CHF_{2015}	
$c_{inv,var}$	5.351e6	CHF_{2015}/MW_e	[2]
$c_{op,fix}$	-	CHF_{2015}/h	
$c_{op,var}$[a]	6.108	CHF_{2015}/MWh_e	[2]
Lifetime	40	y	[2]
GWP100a[b]	4.699	$kgCO_2$-eq./MWh_e	
Impact2002+[b]	1.070e-3	pts/MWh_e	
ES2013[b]	3.486e3	UBP/MWh_e	

[a] O&M assumed as 1 % of c_{inv} based on [2], over 8760 h.
[b] Emissions for construction, operation and end-of-life.

3.6.2 Natural Gas CHP

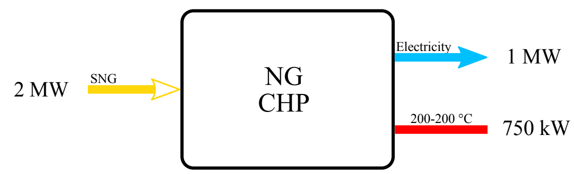

Figure 13: Natural gas Cogeneration of Heat and Power (CHP) unit model.

The CHP unit (Figure 13) in the model has SNG as an input, which is assumed equivalent to fossil NG. It is modeled as a Combined-Cycle Gas Turbine (CCGT), a cycle configuration combining a gas turbine with a bottoming steam cycle to achieve high electrical efficiencies. Efficiency data are taken from [4] for a typical 200-250 MW_e installation in 2035. As a simplification, the output temperature level is chosen high enough to satisfy the heat demand in the model. As CCGT plants in Switzerland are smaller (34-55 MW_e), cost data are taken from [1] for typical installations in Switzerland. Cost and emission data are reported in Table 17.

Table 17: Natural Gas CHP parameters.

	Value	**Units**	**References**
Reference size	34-55	MW_e	[1]
$c_{inv,fix}$	-	CHF_{2015}	
$c_{inv,var}$	1.453e6	CHF_{2015}/MW_e	[1]
$c_{op,fix}$	-	CHF_{2015}/h	
$c_{op,var}$	9.684	CHF_{2015}/MWh_e	[1]
Lifetime	25	y	[4]
$GWP100a_{C,E}$	3.927e5	$kgCO_2$-eq./MW_e	
Impact2002+$_{C,E}$	79.69	pts/MW_e	
$ES2013_{C,E}$	1.519e8	UBP/MW_e	
$GWP100a_O$	-	$kgCO_2$-eq./MWh_{in}	
Impact2002+$_O$	3.570e-3	pts/MWh_{in}	
$ES2013_O$	1.129e4	UBP/MWh_{in}	

3.6.3 Oil and BioOil CHP

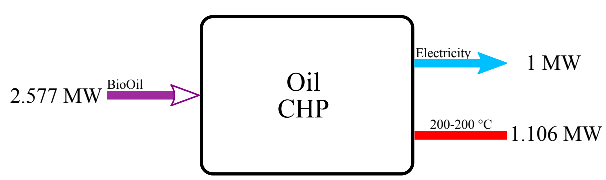

Figure 14: BioOil CHP unit model.

The CHP unit in the model has BioOil as an input (Figure 14). For comparison, also the fossil oil option is reported here. LFO and BioOil are assumed to have the same performance in terms of efficiency. Due to lack of specific data for the technology, efficiency data are taken for a typical 200 kW_e diesel CHP engine [50]. As a simplification, the output temperature level is chosen high enough to satisfy the heat demand in the model. Cost data are taken from [4] for a 2 MW_e NG CHP with the same electrical efficiency as the diesel reference model. Coherently with what written in section 3.3.2, different HH emissions are considered for combustion of fossil LFO and BioOil, due to the higher emissions of the latter. Cost and emission data are reported in Table 18.

Table 18: Oil-BioOil CHP parameters

	Value		Units	References
	LFO	**BioOil**		
Reference size	0.2-2		MW_e	
$c_{inv,fix}$	-		CHF_{2015}	
$c_{inv,var}$ [a]	1.107e6		CHF_{2015}/MW_e	[4]
$c_{op,fix}$	-		CHF_{2015}/h	
$c_{op,var}$ [a]	11.55 [b]		CHF_{2015}/MWh_e	[4]
Lifetime	20		y	[4]
$GWP100a_{C,E}$ [c]	8.319e5		$kgCO_2$-eq./MW_e	
$Impact2002+_{C,E}$ [c]	1.780e2		pts/MW_e	
$ES2013_{C,E}$ [c]	3.530e8		UBP/MW_e	
$GWP100a_O$	-	-	$kgCO_2$-eq./MWh_{in}	
$Impact2002+_O$	6.619e-3 [c]	1.298e-2 [d]	pts/MWh_{in}	
$ES2013_O$	2.026e4 [c]	3.096e4 [d]	UBP/MWh_{in}	

[a] Data for a 2 MW_e NG CHP.
[b] Assuming 4000 h/y of operation.
[c] Due to lack of technology-specific data, calculated based on data for 200 kW_e diesel CHP engine in [50].
[d] Due to lack of LCA data for BioOil combustion, operation assumed equal to combustion in boiler (Table 13).

3.6.4 Wet and dry wood CHP

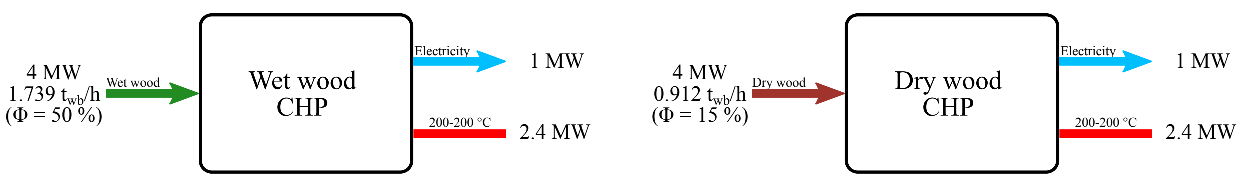

Figure 15: Wet and dry wood CHP unit model.

The wood CHP unit (Figure 15) in the model can have wet ($\Phi = 50$ %) and dry ($\Phi = 15$ %) wood as inputs. The same performance in terms of *wb* efficiency is assumed in the two cases. As a simplification, the output temperature level is chosen high enough to satisfy the heat demand in the model. Efficiency and cost data are taken from [30] for a 5 MW_{th} (2.08 MW_e) biomass CHP-ORC system. Emission data are taken from [50] for a state-of-the-art 6.67 MW_{in} CHP burning wet wood ($\Phi = 52$ %). Due to lack of emission data allowing to differentiate between wet and dry wood combustion, the same values on a *db* are assumed for the two cases. Cost and emission data are reported in Table 19.

Table 19: Wet and dry wood CHP parameters

	Value	**Units**	**References**
Reference size	2.08	MW_e	[30]
$c_{inv,fix}$	-	CHF_{2015}	
$c_{inv,var}$	4.651e6	CHF_{2015}/MW_e	[30]
$c_{op,fix}$	-	CHF_{2015}/h	
$c_{op,var}$ [a]	46.51	CHF_{2015}/MWh_e	[30]
Lifetime	25	y	
$GWP100a_{C,E}$	4.868e5	$kgCO_2$-eq./MW_e	
Impact2002+$_{C,E}$	1.014e2	pts/MW_e	
$ES2013_{C,E}$	2.084e8	UBP/MW_e	
$GWP100a_O$	-	$kgCO_2$-eq./$MWh_{db,in}$	
Impact2002+$_O$	1.615e-2	pts/$MWh_{db,in}$	
$ES2013_O$	1.848e4	UBP/$MWh_{db,in}$	

[a] O&M costs are 4 % of the investment cost over 4000 h/y of operation.

3.7 Storage

The modeling of storage is detailed in the main article (Section 2.2.4). Storage units can have multiple inputs and outputs. This is also exploited in the article to force scenarios. No LCA analysis is performed for the storage units.

3.7.1 SNG storage

Figure 16: SNG storage unit model.

The SNG storage unit is used in the model to force the replacement of NG with SNG. In the model, in fact, it is assumed that SNG is equivalent to fossil NG. Thus, it can be injected into the NG grid. No cost is associated to this storage unit, as it is assumed that the produced SNG can replace imports of fossil NG in Switzerland all-year-round using the existing grid infrastructure.
As shown in Figure 16, the unit has an input (SNG layer) and two outputs (SNG and NG layers). This allows to force scenarios. On the one hand, when SNG replaces fossil NG in the model, only the NG output is activated. On the other hand, when SNG is used for CHP or mobility, only the SNG output is activated together with the corresponding cogeneration and mobility unit models.

3.7.2 Oil and BioOil storage

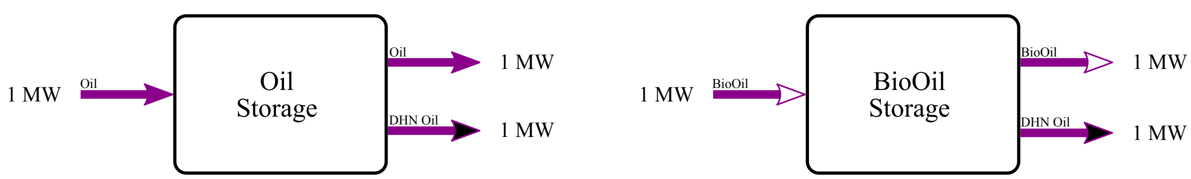

Figure 17: Oil and BioOil storage unit models.

In the model it is assumed that BioOil from fast pyrolysis can only be used in DHN technologies (boiler and CHP). Fossil oil can be used in DHN technologies and also for decentralized heat supply. As shown in Figure 17, the BioOil storage unit has an input (BioOil layer) and two outputs (BioOil and DHN Oil layers). This allows to force scenarios. When the CHP oil unit is used in the system, the DHN oil output is deactivated in order to ensure that all the BioOil is consumed by the CHP unit.
Cost data are taken from [3], who report an estimate from producers data for a 9375 m^3 BioOil storage tank. The data are adapted for fossil oil storage accounting for the different physical properties of the two fuels. Cost data are summarized in Table 20.

Table 20: Oil and BioOil storage tanks parameters

	Value		**Units**	**References**
	LFO	**BioOil**[a]		
Reference size	9.419e4	4.765e4	$\mathrm{MWh_{fuel}}$[b]	
$c_{\mathrm{inv,fix}}$	-		$\mathrm{CHF_{2015}}$	
$c_{\mathrm{inv,var}}$	1.204e1	2.380e1	$\mathrm{CHF_{2015}/MWh_{fuel}}$	[3]
$c_{\mathrm{op,fix}}$	-		$\mathrm{CHF_{2015}/h}$	
$c_{\mathrm{op,var}}$[c]	5.497e-5	1.087e-4	$\mathrm{CHF_{2015}/MWh_{fuel}/h}$	
Lifetime	50		y	

[a] Assuming $LHV = 15.247$ MJ/kg (Section 3.3.2) and density of 1200 kg/m^3 as in [3].
[b] Energy equivalent of the amount of fuel stored.
[c] Assuming O&M as 4 % of investment as for wood storage (Table 21), over 8760 h.

3.7.3 Wood storage

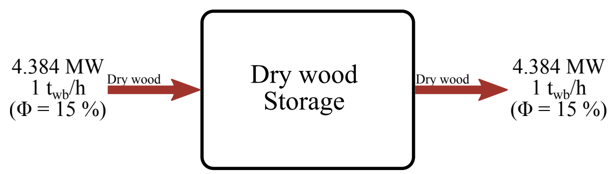

Figure 18: Dry wood storage unit model.

The dry biomass storage model (Figure 18) is based on the "covered storage facility of a pole-frame structure having a metal roof without any infrastructure for biomass drying" presented in [31]. This storage has a maximum height of 6 m. [31] indicates that material losses are 0.5 %/month. Thus, the output storage efficiency is set as $\varepsilon(sto_{out}) = 99.5$ %. Cost data are summarized in Table 21.

Table 21: Dry wood storage parameters

	Value[a]	**Units**	**References**
Reference size	-	$\mathrm{MWh_{fuel}}$[b]	
$c_{\mathrm{inv,fix}}$	-	$\mathrm{CHF_{2015}}$	
$c_{\mathrm{inv,var}}$	2.414e1	$\mathrm{CHF_{2015}/MWh_{fuel}}$	[31]
$c_{\mathrm{op,fix}}$	-	$\mathrm{CHF_{2015}/h}$	
$c_{\mathrm{op,var}}$[c]	1.102e-4	$\mathrm{CHF_{2015}/MWh_{fuel}/h}$	[31]
Lifetime	50	y	

[a] Dry wood density is 235 kg/m^3 for wood chips at $\Phi = 15$ % [6].
[b] Energy equivalent of the amount of fuel stored.
[c] O&M costs are 4 % of investment over 8760 h.

3.8 Waste treatment and District Heating Network

3.8.1 Municipal Solid Waste Incinerator (MSWI)

Figure 19: MSWI unit model.

A general description of the Municipal Solid Waste Incineration (MSWI) of the city of Lausanne ("TRIDEL") is offered in Section 1.1. The MSWI is here represented in a simplified way based on the work by Amblard [18]. As of 2015, the power plant burns both Municipal Solid Waste (MSW) and wet wood to produce steam, which is first expanded in a steam turbine down to 175 °C, and then used for DHN heat supply. In summer, the excess heat is expanded to ambient temperature in a second turbine.
In the model the winter operating mode is assumed for the whole year and no wet wood is burned in the plant. The winter efficiency is calculated based on 2012 data [46] and scaled in order to have only MSW as an input. The waste input is constant all over the year. In the model this is forced by setting the MSW resource as a "process". The first principle efficiency is 74.98 %, leading to a total heat production of 38.65 MW_{th} and a total electricity production of 8.61 MW_e. The share of thermal and electrical production for auto-consumption of the plant are 1.52 % and 27 %, respectively. Cost and emission data are reported in Table 22.

Table 22: MSWI parameters

	Value	**Units**	**References**
Reference size	20/60	MW_e/MW_{th}	[46]
$c_{inv,fix}$	1.394e8/1.324e8[a]	CHF_{2015}	[46]
$c_{inv,var}$	-	CHF_{2015}/MW	
$c_{op,fix}$	-	CHF_{2015}/h	
$c_{op,var}$	5.809[b]	CHF_{2015}/MWh	[46]
Lifetime	30/17.5[a]	y	[46]
$GWP100a_{C,E}$[c]	1.838e7	$kgCO_2$-eq.	
$Impact2002+_{C,E}$[c]	2.866e3	pts	
$ES2013_{C,E}$[c]	6.939e9	UBP	
$GWP100a_O$[d]	-	$kgCO_2$-eq./MWh_{in}	
$Impact2002+_O$	4.295e-3	pts/MWh_{in}	
$ES2013_O$	4.810e3	UBP/MWh_{in}	

[a] First value is for the power plant, second value for the electromechanical installation (turbines).
[b] Includes O&M and salaries. Calculated over the total output, adding thermal and electrical production.
[c] Total emissions for construction and end-of-life of a typical MSWI in Switzerland.
[d] GWP impact related to the treatment of MSW in an incineration plant, including auxiliary emissions due to the operation of the plant, are attributed to the MSW resource (Table 4).

3.8.2 Waste Water Treatment Plant (WWTP)

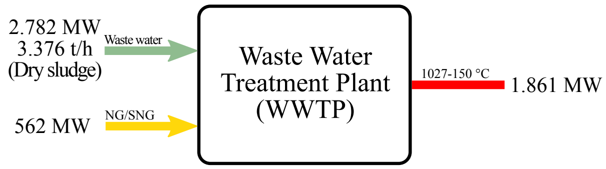

Figure 20: WWTP unit model.

In the WWTP of Lausanne ("STEP"), the dry sludge obtained from the treatment of waste water is burned in a 4 MW_{th} boiler supplying heat to the DHN. Only the boiler is modeled in this work. NG is also needed in the combustion process. The model represented in Figure 20 is based on data for the power plant operation in 2012 [12]. In that year, the boiler processed 29.58 kt of dry sludge and delivered 16.3 GWh_{th} to the DHN as baseload. This is the net heat production, accounting for the share of heat needed for autoconsumption (4.95 %). The global first principle efficiency was 58.6 % and the capacity factor 84.7 % (309 days of operation). In the work by Amblard [18] seasonal variations are accounted for in the WWTP model. As these variations are not significant, it is here assumed for simplicity that the power plant works with a constant input over the whole year. In the model this is forced by setting the waste water resource as a "process". Operating emissions are not accounted for. Cost and emission data are reported in Table 23.

Table 23: WWTP parameters

	Value	**Units**	**References**
Reference size	4	MW_{th}	[18]
$c_{inv,fix}$	9.009e6[a]	CHF_{2015}	[33]
$c_{inv,var}$	-	CHF_{2015}/MW_{th}	
$c_{op,fix}$	-	CHF_{2015}/h	
$c_{op,var}$	4.030e1	CHF_{2015}/MWh_{th}	Personal communication, SiL
Lifetime	25	y	
$GWP100a_{C,E}$[b]	5.947e7	$kgCO_2$-eq.	
$Impact2002+_{C,E}$[b]	1.062e4	pts	
$ES2013_{C,E}$[b]	2.374e10	UBP	

[a] Calculated based on the annual amortization value.
[b] Total emissions for construction and end-of-life of a typical WWTP in Switzerland.

3.8.3 District Heating Network (DHN)

The DHN unit in the model is used to transfer the heat produced by the centralized technologies to the heat demand units. The network is modeled based on the data available for Lausanne for the year 2012. In that year, the total length of the network was 101 km, delivering 364.7 GWh_{th}/y with 14.4 % losses [18]. An increase of 3 km/y is assumed, leading to a total length of 170 km in 2035. As detailed in Section 1.2, it is projected that the share of heat demand supplied by the DHN in 2035 is 45 %. The temperature of Lausanne's DHN is quite high (130-70 °C) and losses are fixed at 15 % all-year-round. Emissions related to construction are based on the impact of needed materials (steel, foramed poliuretane, cement, concrete, diesel), which are taken from [29]. Operating emissions are not accounted for. Cost and emission data are reported in Table 24.

Table 24: DHN parameters

	Value	**Units**	**References**
Reference size	170	km	[18]
$c_{\text{inv,fix}}$	5.100e8	CHF_{2015}	Personal communication, SiL
$c_{\text{inv,var}}$	-	CHF_{2015}/MW	
$c_{\text{op,fix}}$	1.553e2[a]	CHF_{2015}/h	Personal communication, SiL
$c_{\text{op,var}}$	-	CHF_{2015}/MWh	
Lifetime	50	y	Personal communication, SiL
GWP100a$_{C,E}$[b]	3.994e5	kgCO_2-eq.	[29]
Impact2002+$_{C,E}$[b]	5.448e1	pts	[29]
ES2013$_{C,E}$[b]	1.256e8	UBP	[29]

[a] 8 CHF/m/y, over 8760 h.

[b] Total emissions for the construction and end-of-life of the network, based on the needed materials (steel, foramed poliuretane, cement, concrete, diesel) from [29].

3.9 Mobility

This section covers the unit models for private and public mobility. The main difference with the other models is that the lifetime of the technologies is here expressed in terms of total covered distance. Thus, investment costs are annualized by fixing this parameter, without the need of assuming a lifetime in terms of time duration. Mobility demand is defined in Section 3.2.

3.9.1 Private mobility

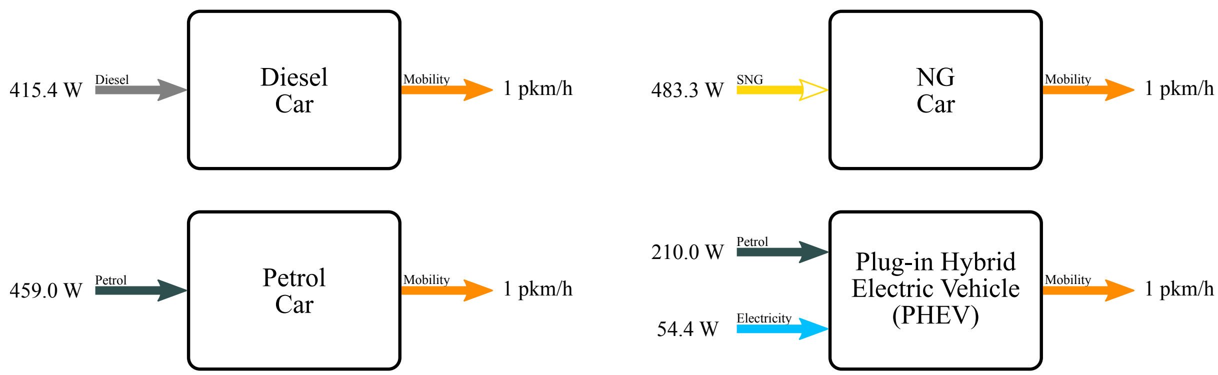

Figure 21: Private mobility unit models.

Figure 21 shows the four types of vehicles modeled in this work: NG cars, diesel cars, petrol cars, Plug-in Hybrid Electric Vehicles (PHEVs). The conversion efficiencies reported in the figure are taken for "EURO 5" vehicles from [50], with the exception of the PHEV, which is based on data for a typical 2015 vehicle from [47]. For the PHEV, in the model it is assumed that electricity is used to cover 40 % of the total distance and petrol to cover the remaining 60 %. If running only on electricity the PHEV consumes 135.9 Wh/pkm, whereas if running only on petrol the consumption is 349.9 Wh/pkm. The lifetime of all vehicles is 150000 km [15] and the average occupancy is 1.6 passenger/vehicle (data for the year 2010 in Switzerland, from [39]).

In the model it is assumed that 50 % of the private mobility demand is supplied by PHEVs, with the remaining share being supplied by diesel cars. The NG car can have only SNG as an input, assuming the same perfomance in terms of efficiency, cost and emissions (for GWP emissions related to combustion are allocated to the resources). In the scenarios in which SNG is used in mobility, NG cars replace part of the diesel share.

Cost data are estimated from [44] for typical vehicles in Switzerland. The investment cost for a diesel car is 35000 CHF_{2015}. The petrol car is assumed to be 5 % cheaper, while the NG and PHEV car assumed to be 10 % and 20 % more expensive than the diesel car, respectively. O&M costs are 0.212 CHF_{2015}/km for all vehicles. Emission data are summarized in Table 25.

3.9.2 Public mobility

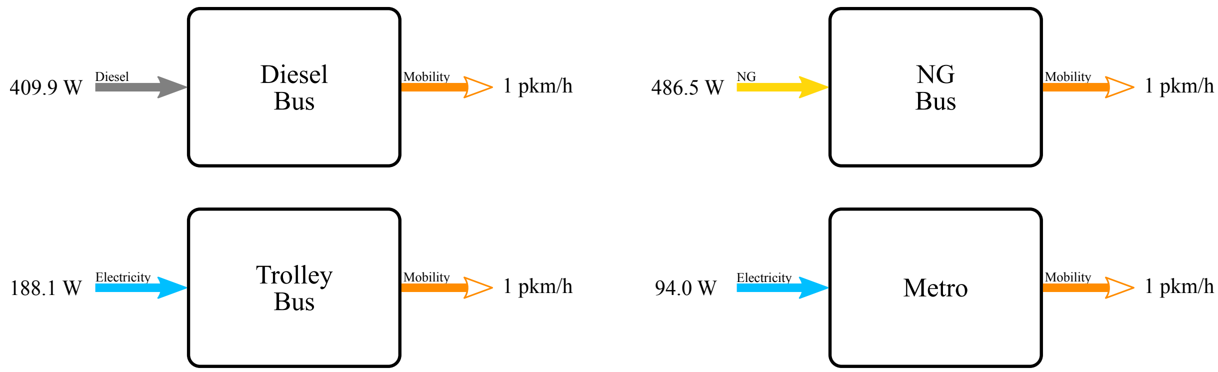

Figure 22: Public mobility unit models.

Figure 22 shows the four means of public transport modeled in this work: NG buses, diesel buses, trolley buses (electric), metro. The conversion efficiencies reported in the figure are calculated from Amblard [18] based on the energy consumption of the Lausanne fleet in the year 2012 [45]. As there are no NG buses in Lausanne, the NG bus consumption is determined based on the diesel bus consumption multiplied by the ratio between the fuel economies of the correspondent private mobility models.
Data for cost, occupancy and lifetime are reported in Table 26, together with the share of public pkm covered by each technology (fixed in the model). Emission data are summarized in Table 25.

Table 25: Private and public mobility model emission parameters.

	Technology	LCA (C,E)[a] GWP100a [kgCO$_2$-eq./v]	Impact2002+ [pts/v]	ES2013 [UBP/v]	LCA (O) GWP100a[b] [kgCO$_2$-eq./MWh$_{\text{in}}$]	Impact2002+[c] [pts/MWh$_{\text{in}}$]	ES2013[c] [UBP/MWh$_{\text{in}}$]
Private	Diesel car[d]	1.157e4	2.842	4.978e6	3.254e1	3.361e-2	6.420e4
	Petrol car[d]	1.146e4	2.794	4.919e6	2.955e1	1.934e-2	2.542e4
	NG car[d]	1.146e4	2.794	4.919e6	3.183e1	1.811e-2	2.229e4
	PHEV[e]	9.883e3	3.158	4.781e6	6.307e1	2.534e-2	6.207e4
Public	Diesel Bus	3.993e4	9.426	1.832e7	3.990e1	5.977e-2	1.625e5
	NG bus[f]	3.993e4	9.426	1.832e7	3.030e1	1.799e-2	2.214e4
	Trolley bus	3.993e4	9.426	1.832e7	9.331e1	2.554e-2	6.329e4
	Metro[g]	6.652e5	1.756e2	3.414e8	7.217e1	1.559e-2	4.166e4

[a] Emissions related to construction and end-of-life of one vehicle (v).
[b] Operating impact per MWh of input fuel, excluding fuel combustion and electricity consumption (allocated to resources).
[c] Operating impact per MWh of input fuel, including fuel combustion, excluding electricity.
[d] Construction emissions for a 1600 kg vehicle from [50].
[e] Construction emissions for a 918 kg electric vehicle plus a 262 kg battery. Battery is replaced after 100000 km [50]. For the PHEV a 60 % / 40 % petrol/electricity share is assumed. Operating emissions in the table are per MWh$_{\text{e}}$ (electricity only mode). For emissions when running on petrol, petrol car values are used.
[f] As no data are available for NG buses emissions, construction emissions are assumed equal to Diesel bus. Operating impacts are calculated assuming same impact of NG cars (per pkm) and scaled according to the bus fuel economy.
[g] Data for a regional passenger train in Switzerland [50]

Table 26: Public mobility model parameters.

Technology	**Share** [%]	**Occupancy** [p/v]	$\mathbf{c_{inv,var}}$ [CHF$_{2015}$/v]	$\mathbf{c_{op,var}}$ [CHF$_{2015}$/km]	**Lifetime** [km]
Diesel Bus	5	16 [15]	5.250e5 [48]	6.057e-1 [48]	1.00e6 [15]
NG bus[a]	5	16 [15]	5.775e5	6.057e-1	1.00e6
Trolley bus	35	26 [15]	1.171e6 [48]	1.040 [48]	1.42e6 [15]
Metro	55	63 [18][b]	4.758e6 [10]	1.040[c]	1.12e6 [15][d]

[a] Due to lack of data for NG bus, investment cost assumed 10 % higher than diesel bus. O&M costs and emissions assumed equal to diesel bus.
[b] Based on 2012 data for Lausanne from [45].
[c] Assumed equal to diesel bus. Does not include the cost for the needed infrastructure.
[d] Data for a tram.

4 Additional results

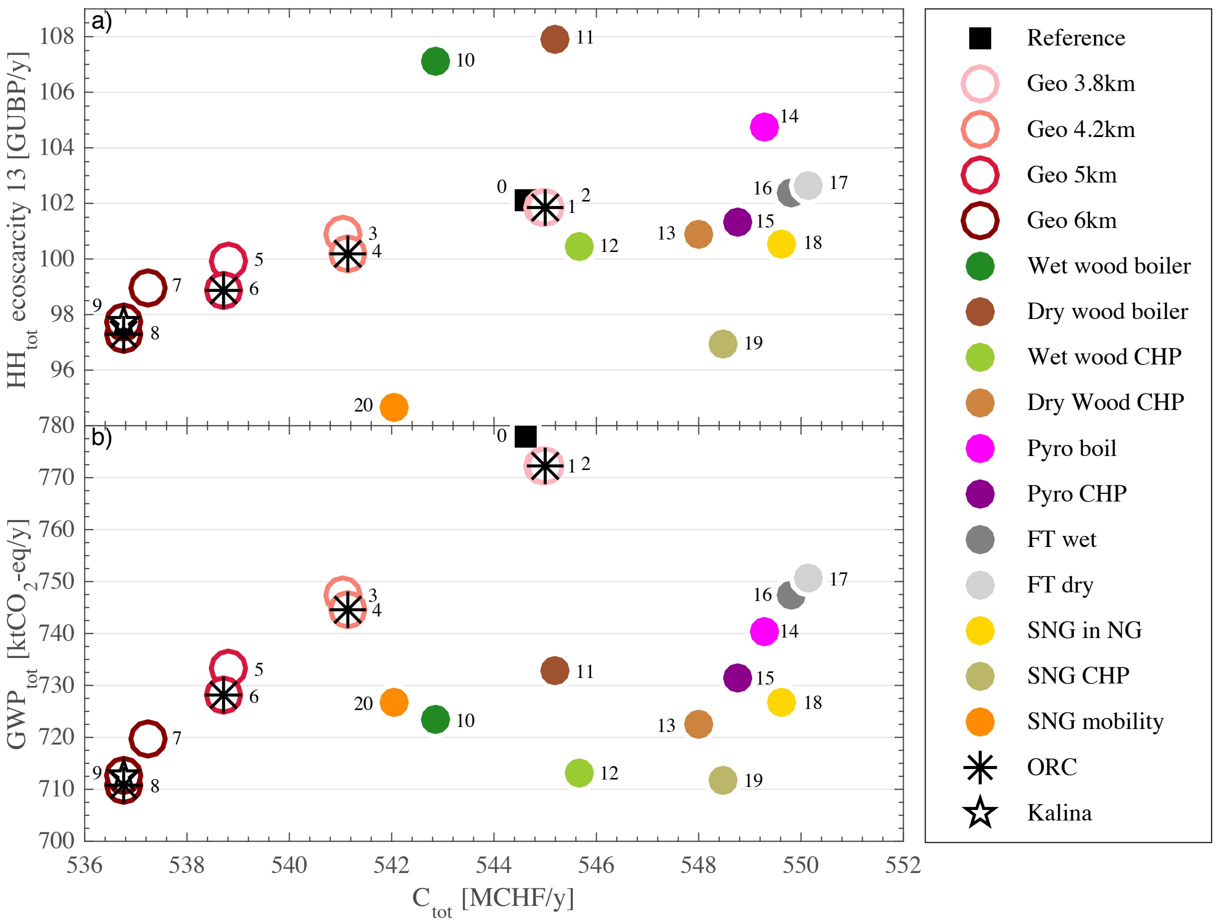

Figure 23: Results of the individual scenarios listed in Table 1 (main article): individual assessment of geothermal and biomass options (1 GUPB = 1e9 UBP). The subplots depict HH_{tot} (a) and GWP_{tot} (b) against the total annual cost C_{tot}, respectively.

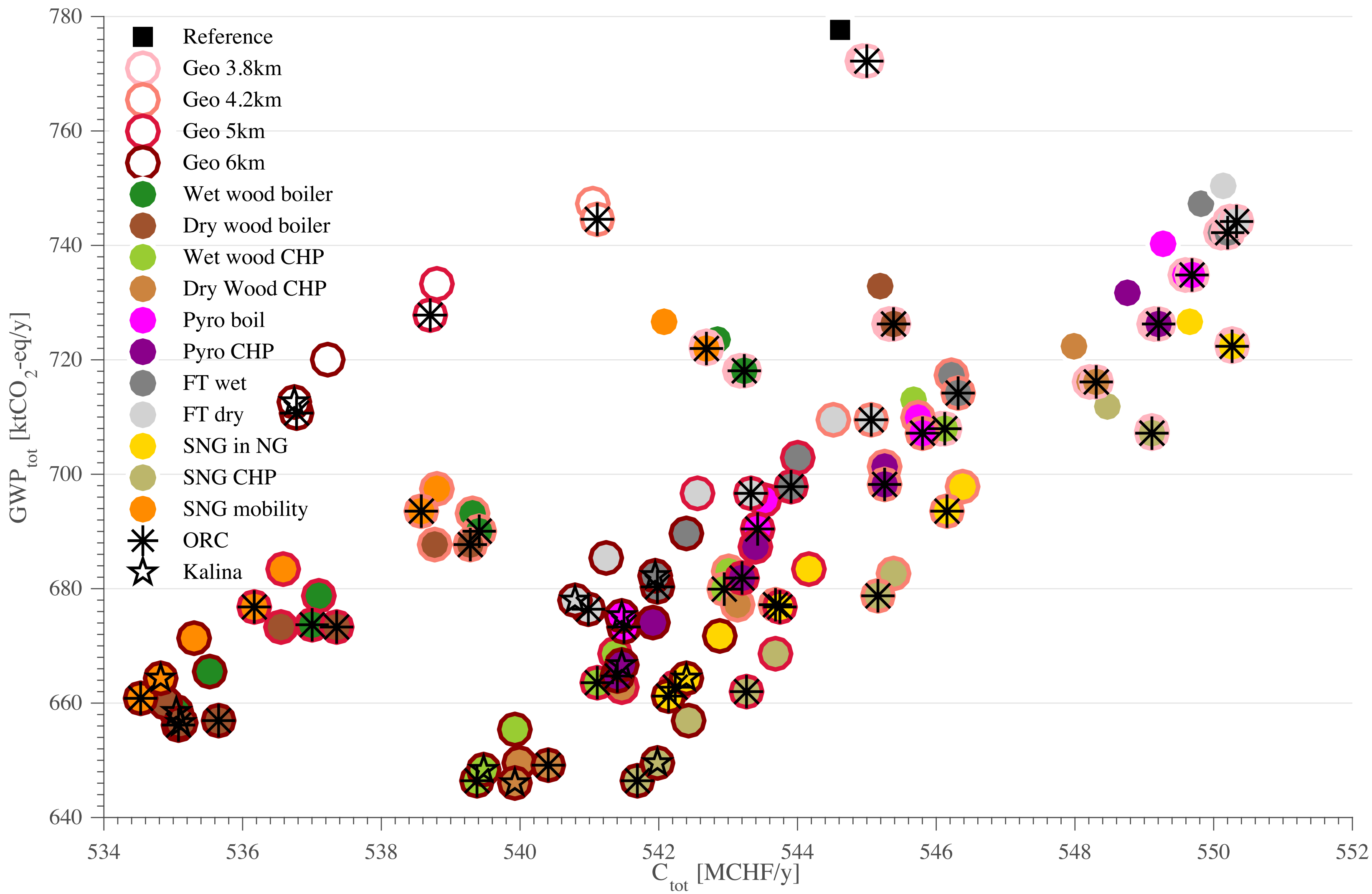

Figure 24: Results for all scenarios: Total annual cost vs GWP emissions.

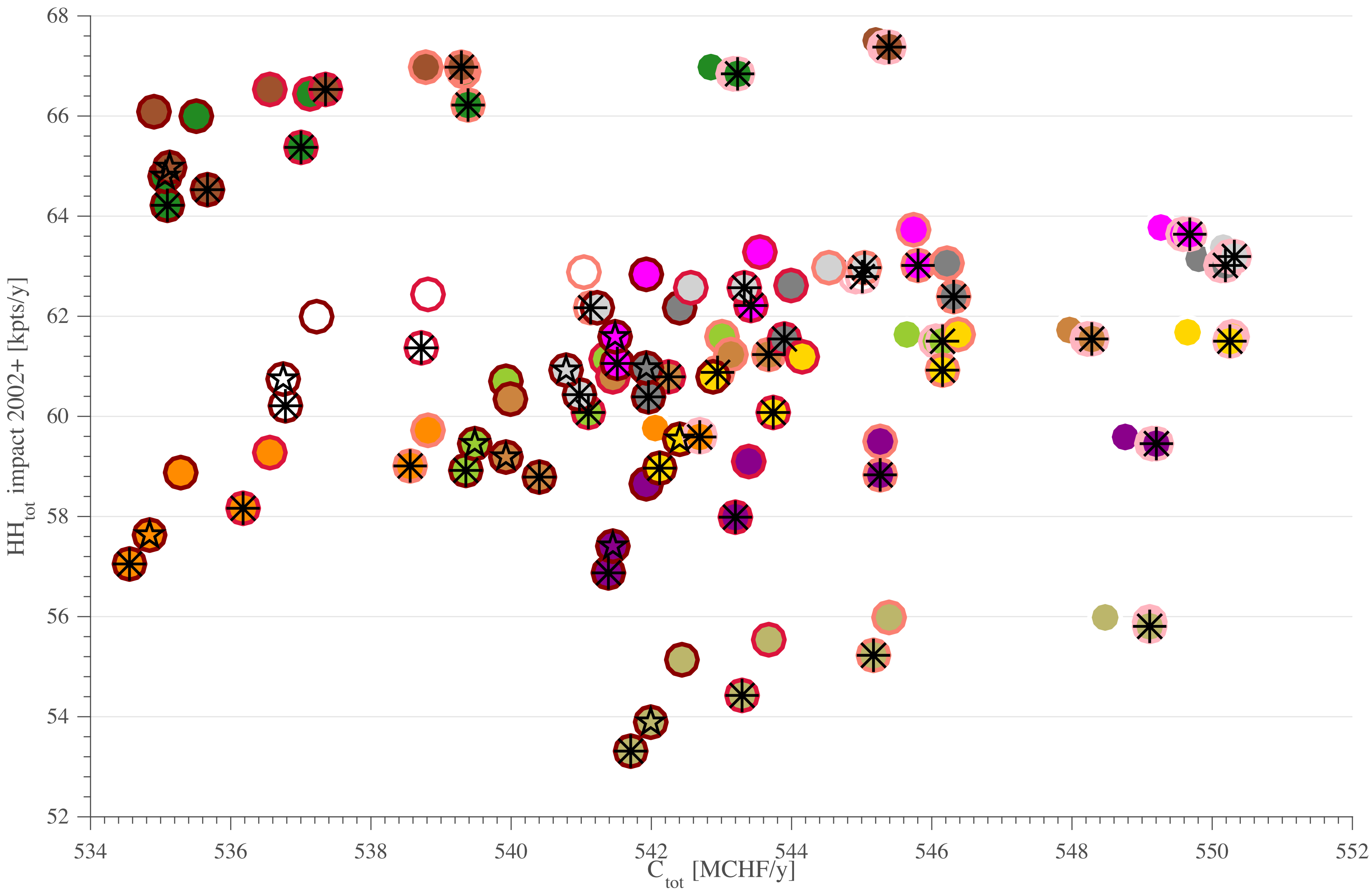

Figure 25: Results for all scenarios: Total annual cost vs HH emissions (for legend see Figure 24).

Table 27: δPI calculated for each performance indicator (Eq. 19 of the main article). Performance of each scenario with respect to the reference (scenario 0).

#	**Biomass**	**Geothermal**	δC_{tot} [MCHF/y]	δGWP_{tot} [ktCO$_2$-eq./y]	δHH_{tot} **Impact2002+** [kpts/y]	δHH_{tot} **ES2013** [GUPB/y]
0	-	-	0	0	0	0
1	-	3.8 km Direct use	0.31	-5.38	-0.14	-0.32
2	-	3.8 km ORC	0.39	-5.38	-0.14	-0.32
3	-	4.2 km Direct use	-3.58	-30.4	-0.08	-1.29
4	-	4.2 km ORC	-3.50	-33.2	-0.76	-1.92
5	-	5 km Direct use	-5.80	-44.6	-0.52	-2.24
6	-	5 km ORC	-5.90	-49.8	-1.60	-3.27
7	-	6 km Direct use	-7.40	-57.8	-0.97	-3.15
8	-	6 km ORC	-7.83	-67.0	-2.75	-4.87
9	-	6 km Kalina	-7.86	-65.0	-2.20	-4.38
10	Wet wood boiler	-	-1.77	-54.4	4.03	4.96
11	Dry wood boiler	-	0.58	-45.0	4.58	5.78
12	Wet wood CHP	-	1.04	-64.5	-1.30	-1.72
13	Dry wood CHP	-	3.36	-55.4	-1.24	-1.28
14	Pyrolysis boiler	-	4.66	-37.5	0.84	2.59
15	Pyrolysis CHP	-	4.14	-46.2	-3.38	-0.84
16	Wet Wood FT	-	5.19	-30.3	0.21	0.24
17	Dry Wood FT	-	5.53	-27.1	0.42	0.54
18	SNG in NG	-	5.03	-51.0	-1.26	-1.62
19	SNG CHP	-	3.86	-66.0	-6.96	-5.23
20	SNG Mobility	-	-2.55	-51.2	-3.20	-7.47
(1,10)	Wet wood boiler	3.8 km Direct use	-1.44	-59.8	3.89	4.64
(2,10)	Wet wood boiler	3.8 km ORC	-1.37	-59.8	3.89	4.64
(3,10)	Wet wood boiler	4.2 km Direct use	-5.29	-84.7	3.96	3.67
(4,10)	Wet wood boiler	4.2 km ORC	-5.22	-87.6	3.28	3.04
(5,10)	Wet wood boiler	5 km Direct use	-7.50	-99.0	3.51	2.72
(6,10)	Wet wood boiler	5 km ORC	-7.60	-104.2	2.43	1.69
(7,10)	Wet wood boiler	6 km Direct use	-9.10	-112.2	3.06	1.81
(8,10)	Wet wood boiler	6 km ORC	-9.53	-121.4	1.29	0.09
(9,10)	Wet wood boiler	6 km Kalina	-9.56	-119.4	1.83	0.58
(1,11)	Dry wood boiler	3.8 km Direct use	0.70	-51.3	4.41	5.40
(2,11)	Dry wood boiler	3.8 km ORC	0.77	-51.3	4.41	5.40
(3,11)	Dry wood boiler	4.2 km Direct use	-5.85	-90.1	4.04	3.48
(4,11)	Dry wood boiler	4.2 km ORC	-5.32	-90.1	4.05	3.48
(5,11)	Dry wood boiler	5 km Direct use	-8.06	-104.4	3.60	2.53
(6,11)	Dry wood boiler	5 km ORC	-7.28	-104.4	3.60	2.54
(7,11)	Dry wood boiler	6 km Direct use	-9.72	-117.6	3.15	1.62
(8,11)	Dry wood boiler	6 km ORC	-8.96	-120.6	1.57	0.33
(9,11)	Dry wood boiler	6 km Kalina	-9.50	-121.3	2.03	0.63
(1,12)	Wet wood CHP	3.8 km Direct use	1.45	-69.9	-1.44	-2.03
(2,12)	Wet wood CHP	3.8 km ORC	1.52	-69.9	-1.44	-2.03
(3,12)	Wet wood CHP	4.2 km Direct use	-1.60	-94.8	-1.37	-2.98
(4,12)	Wet wood CHP	4.2 km ORC	-1.66	-97.7	-2.05	-3.61
(5,12)	Wet wood CHP	5 km Direct use	-3.26	-109.0	-1.80	-3.91

Table 27: δPI calculated for each performance indicator (Eq. 19 of the main article). Performance of each with respect to the reference (scenario 0).

#	Biomass	Geothermal	δC_{tot} [MCHF/y]	δGWP_{tot} [ktCO$_2$-eq./y]	δHH_{tot} Impact2002+ [kpts/y]	δHH_{tot} ES2013 [GUPB/y]
(6,12)	Wet wood CHP	5 km ORC	-3.50	-114.2	-2.88	-4.94
(7,12)	Wet wood CHP	6 km Direct use	-4.68	-122.2	-2.25	-4.81
(8,12)	Wet wood CHP	6 km ORC	-5.25	-131.4	-4.03	-6.54
(9,12)	Wet wood CHP	6 km Kalina	-5.14	-129.5	-3.48	-6.04
(1,13)	Dry wood CHP	3.8 km Direct use	3.60	-61.7	-1.41	-1.65
(2,13)	Dry wood CHP	3.8 km ORC	3.68	-61.7	-1.41	-1.65
(3,13)	Dry wood CHP	4.2 km Direct use	-1.48	-100.7	-1.73	-3.51
(4,13)	Dry wood CHP	4.2 km ORC	-0.95	-100.7	-1.73	-3.50
(5,13)	Dry wood CHP	5 km Direct use	-3.15	-114.9	-2.17	-4.44
(6,13)	Dry wood CHP	5 km ORC	-2.37	-114.9	-2.16	-4.43
(7,13)	Dry wood CHP	6 km Direct use	-4.63	-128.1	-2.62	-5.34
(8,13)	Dry wood CHP	6 km ORC	-4.21	-128.5	-4.15	-6.51
(9,13)	Dry wood CHP	6 km Kalina	-4.69	-131.8	-3.75	-6.35
(1,14)	Pyrolysis boiler	3.8 km Direct use	4.98	-42.9	0.71	2.27
(2,14)	Pyrolysis boiler	3.8 km ORC	5.06	-42.9	0.71	2.27
(3,14)	Pyrolysis boiler	4.2 km Direct use	1.11	-67.8	0.77	1.30
(4,14)	Pyrolysis boiler	4.2 km ORC	1.18	-70.7	0.09	0.67
(5,14)	Pyrolysis boiler	5 km Direct use	-1.08	-82.1	0.33	0.35
(6,14)	Pyrolysis boiler	5 km ORC	-1.19	-87.3	-0.76	-0.68
(7,14)	Pyrolysis boiler	6 km Direct use	-2.67	-95.3	-0.13	-0.56
(8,14)	Pyrolysis boiler	6 km ORC	-3.11	-104.5	-1.90	-2.28
(9,14)	Pyrolysis boiler	6 km Kalina	-3.14	-102.5	-1.36	-1.79
(1,15)	Pyrolysis CHP	3.8 km Direct use	4.52	-51.5	-3.51	-1.15
(2,15)	Pyrolysis CHP	3.8 km ORC	4.60	-51.5	-3.51	-1.15
(3,15)	Pyrolysis CHP	4.2 km Direct use	0.64	-76.5	-3.45	-2.12
(4,15)	Pyrolysis CHP	4.2 km ORC	0.65	-79.4	-4.13	-2.76
(5,15)	Pyrolysis CHP	5 km Direct use	-1.22	-90.6	-3.85	-2.99
(6,15)	Pyrolysis CHP	5 km ORC	-1.42	-95.8	-4.94	-4.04
(7,15)	Pyrolysis CHP	6 km Direct use	-2.69	-103.7	-4.29	-3.87
(8,15)	Pyrolysis CHP	6 km ORC	-3.22	-113.0	-6.07	-5.61
(9,15)	Pyrolysis CHP	6 km Kalina	-3.16	-110.9	-5.52	-5.10
(1,16)	Wet Wood FT	3.8 km Direct use	5.50	-35.6	0.07	-0.08
(2,16)	Wet Wood FT	3.8 km ORC	5.58	-35.6	0.07	-0.08
(3,16)	Wet Wood FT	4.2 km Direct use	1.61	-60.6	0.13	-1.05
(4,16)	Wet Wood FT	4.2 km ORC	1.69	-63.4	-0.55	-1.68
(5,16)	Wet Wood FT	5 km Direct use	-0.61	-74.9	-0.31	-2.00
(6,16)	Wet Wood FT	5 km ORC	-0.71	-80.1	-1.39	-3.03
(7,16)	Wet Wood FT	6 km Direct use	-2.21	-88.1	-0.77	-2.91
(8,16)	Wet Wood FT	6 km ORC	-2.64	-97.3	-2.54	-4.63
(9,16)	Wet Wood FT	6 km Kalina	-2.67	-95.3	-2.00	-4.14
(1,17)	Dry Wood FT	3.8 km Direct use	5.63	-33.5	0.26	0.16
(2,17)	Dry Wood FT	3.8 km ORC	5.70	-33.5	0.26	0.16
(3,17)	Dry Wood FT	4.2 km Direct use	-0.09	-68.2	0.03	-1.46
(4,17)	Dry Wood FT	4.2 km ORC	0.44	-68.2	0.03	-1.45

Table 27: δPI calculated for each performance indicator (Eq. 19 of the main article). Performance of each with respect to the reference (scenario 0).

#	**Biomass**	**Geothermal**	$\delta \boldsymbol{C_{tot}}$ [MCHF/y]	$\delta \boldsymbol{GWP_{tot}}$ [ktCO$_2$-eq./y]	$\delta \boldsymbol{HH_{tot}}$ **Impact2002+** [kpts/y]	$\delta \boldsymbol{HH_{tot}}$ **ES2013** [GUPB/y]
(5,17)	Dry Wood FT	5 km Direct use	-2.06	-81.0	-0.37	-2.31
(6,17)	Dry Wood FT	5 km ORC	-1.28	-81.0	-0.36	-2.30
(7,17)	Dry Wood FT	6 km Direct use	-3.37	-92.4	-0.77	-3.10
(8,17)	Dry Wood FT	6 km ORC	-3.63	-101.1	-2.53	-4.79
(9,17)	Dry Wood FT	6 km Kalina	-3.83	-99.7	-2.00	-4.33
(1,18)	SNG in NG	3.8 km Direct use	5.65	-55.0	-1.36	-1.85
(2,18)	SNG in NG	3.8 km ORC	5.65	-55.4	-1.44	-1.93
(3,18)	SNG in NG	4.2 km Direct use	1.76	-79.9	-1.30	-2.82
(4,18)	SNG in NG	4.2 km ORC	1.53	-84.2	-2.02	-3.54
(5,18)	SNG in NG	5 km Direct use	-0.46	-94.2	-1.74	-3.77
(6,18)	SNG in NG	5 km ORC	-0.87	-100.8	-2.86	-4.89
(7,18)	SNG in NG	6 km Direct use	-1.75	-106.0	-2.15	-4.59
(8,18)	SNG in NG	6 km ORC	-2.49	-116.6	-3.96	-6.40
(9,18)	SNG in NG	6 km Kalina	-2.21	-113.2	-3.38	-5.82
(1,19)	SNG CHP	3.8 km Direct use	4.49	-70.0	-7.05	-5.46
(2,19)	SNG CHP	3.8 km ORC	4.48	-70.4	-7.13	-5.53
(3,19)	SNG CHP	4.2 km Direct use	0.77	-94.9	-6.99	-6.41
(4,19)	SNG CHP	4.2 km ORC	0.54	-99.1	-7.71	-7.13
(5,19)	SNG CHP	5 km Direct use	-0.93	-109.1	-7.41	-7.32
(6,19)	SNG CHP	5 km ORC	-1.34	-115.6	-8.53	-8.44
(7,19)	SNG CHP	6 km Direct use	-2.18	-120.9	-7.82	-8.14
(8,19)	SNG CHP	6 km ORC	-2.92	-131.5	-9.63	-9.95
(9,19)	SNG CHP	6 km Kalina	-2.64	-128.1	-9.05	-9.37
(1,20)	SNG Mobility	3.8 km Direct use	-1.93	-55.2	-3.29	-7.70
(2,20)	SNG Mobility	3.8 km ORC	-1.94	-55.6	-3.37	-7.78
(3,20)	SNG Mobility	4.2 km Direct use	-5.82	-80.1	-3.23	-8.67
(4,20)	SNG Mobility	4.2 km ORC	-6.05	-84.3	-3.95	-9.39
(5,20)	SNG Mobility	5 km Direct use	-8.04	-94.4	-3.67	-9.62
(6,20)	SNG Mobility	5 km ORC	-8.45	-101.0	-4.80	-10.74
(7,20)	SNG Mobility	6 km Direct use	-9.33	-106.2	-4.09	-10.44
(8,20)	SNG Mobility	6 km ORC	-10.07	-116.8	-5.90	-12.25
(9,20)	SNG Mobility	6 km Kalina	-9.79	-113.4	-5.32	-11.67

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